Analysis and evaluation of different types of test surrogate employed in the dynamic performance testing of fall-arrest equipment

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Analysis and evaluation of different types of test surrogate employed in the dynamic performance testing of fall-arrest equipment

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Over recent decades, workers have been protecting themselves from the harmful effects of falling from a height, by using fall-arresting systems (FAS). FAS limit the gravitational plummet resulting from an accidental fall, which is achieved by decelerating and stopping the worker in a relatively short distance, hence the term "fall-arrest".

Testing of FAS to confirm the safety and performance of particular designs has, and remains to be a vital part of the validation process, whether statutory, ethical, for research purposes or in conformance with other requirements. In particular, dynamic performance testing, or "drop testing", as the method has became known, simulates an arrested fall by using a test surrogate in place of a human being, and plays a central part in the assessment of FAS designs.

Over the course of time, and on an international basis, different types of test surrogate have been used for different reasons, and these have evolved in response to testing philosophy and experiences. The main problem posed by using test surrogates is that of understanding how the results of testing compare with the results of identical tests if they had been performed with a human being. Are the results representative, and if so, to what degree? And does one type of test surrogate produce more representative results than the other?

Despite previous studies, a number of interrelated issues have grown unchecked over the years, as a result of research being curtailed in this subject area. There is still considerable confusion and a lack of technical information in the fall-arrest market in regard to the appropriateness of test surrogates, test methods, and what the results of these tests actually mean, especially for those organisations that use FAS. This literature review studies previous research, draws conclusions, and presents recommendations for further work.

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SUMMARY

Over 120 articles, reports and research papers from various National, European and International sources were scrutinised, for the purposes of studying the issues that arise as a result of using different kinds of test surrogate in the dynamic performance testing of fall-arresting systems (FAS). The results of this study have been presented as a literature review, which draws conclusions, and also presents directions and recommendations for further work.

Testing of FAS to confirm the safety and performance of particular designs has, and remains to be a vital part of the validation process, whether statutory, ethical, for research purposes or in conformance with other requirements. In particular, dynamic performance testing, or “drop testing”, as the method became known, simulates an arrested fall by using a test surrogate in place of a human being, and plays a central part in the assessment of FAS designs.

Over the course of time, and on an international basis, different types of test surrogate have been used for different reasons, and these have evolved in response to testing philosophy and experiences. The main problem posed by using test surrogates is that of understanding how the results of testing compare with the results of identical tests if they had been performed with a human being. Are the results representative, and if so, to what degree? And does one type of test surrogate produce more representative results than the other?

The characteristics between the different types of test surrogate were analysed and compared in regard to their relevance to drop testing, the type of test results they produce, what information can be derived, and the advantages, disadvantages and limitations of the type of test. Various interrelated issues were examined. Typically, these included:

- test repeatability
- bio-fidelity
- costs of surrogate acquisition and use
- FAS prone to significant performance variations attributable to choice of surrogate
- relating surrogate deficiency and test problems back to accidents or laboratory test failures
- testing of complete FAS compared with testing of individual fall-arrest components
- user mass in excess of that governed by standards-based testing
- appropriateness of standards-based testing in relation to how FAS are used in the field.

Other subjects which are closely associated with the project were mentioned in the report where appropriate. This does not mean that a full exposition has been undertaken on these subjects, examples of which include:

- male and female gender issues
- whole human body impact tolerance to acceleration, jolt / jerk, duration of acceleration, direction of acceleration, and localised accelerations of parts of the body.
1. INTRODUCTION

1.1 PURPOSE

The purpose of the project was to make a study of the issues that arise as a result of using different kinds of test surrogate in the dynamic performance testing of fall-arresting systems (FAS). This was to be achieved by analysing available literature, reports and other sources of information, and recording the salient details as a literature review. Related information and possible recommendations for further work were to be included.

1.2 BACKGROUND

For a period of over fifty years in the United Kingdom, Shand (1960), and for over seventy years in the USA, Rose Manufacturing Company (1993), workers have been protecting themselves from the harmful effects of falling from a height, by using FAS. FAS limit the gravitational plummet resulting from a fall, which is achieved by decelerating and stopping the worker in a relatively short distance, hence the term “fall-arrest”.

Testing of FAS to confirm the safety and performance of particular designs has, and remains to be a vital part of the validation process, whether statutory, ethical, for research purposes or in conformance with other requirements. In particular, dynamic performance testing, or “drop testing”, as the method became known, simulates an arrested fall by using a test surrogate in place of a human being, and plays a central part in the assessment of FAS designs.

Over the course of time, and on an international basis, different types of test surrogate have been used for different reasons, and these have evolved in response to testing philosophy and experiences. The main problem posed by using test surrogates is that of understanding how the results of testing compare with the results of identical tests if they had been performed with a human being. Are the results representative, and if so, to what degree? And does one type of test surrogate produce more representative results than the other?

Despite previous studies, a number of interrelated issues have grown unchecked over the years, as a result of research being curtailed in this subject area. There is still considerable confusion and a lack of technical information in the fall-arrest market in regard to the appropriateness of test surrogates, test methods, and what the results of these tests actually mean, especially for those organisations that use FAS.

1.3 PROJECT APPROACH

The project approach involved:

- a search for relevant literature
- obtaining information from enquiries and visits
- utilisation of available test information
- collecting, analysing and correlating data
- formulating a literature review, with directions and recommendations for future work.
A computerised search was undertaken with the assistance of the British Library Document Supply Centre (BLDSC), which has access to at least 7 million books, journals, reports and theses, covering almost every subject in every language. This was supplemented with other computerised searches of on-line academic databases including BIDS, EBSCO, OCLC, COPAC and COMPENDEX.

The search strategy used a large variety of key words, and cited a number of known authors, but as anticipated through the experience of other searches in the fall-arrest field, the yield of specifically pertinent titles was small, even when extending the time-envelope of the search over a number of decades. As a result of this, restricted searches were also made in other impact biomechanics fields such as those concerning motor vehicle and aircraft passenger restraints, parachutes, and aircraft ejection seats, especially where these topics had been referred to in fall-arrest papers, and where authors had been involved in both fall-arrest and aerospace or motor vehicle studies at some point. Scrutiny of the yielded information revealed circumstances where similar test surrogate criteria apply, and those where useful comparisons could be drawn. In fact it would seem that a great deal of fall-arrest knowledge has drawn on previous aerospace research.

Key bibliographic references in all reviewed papers were searched for as far back as 1919.

Some reports on fall-arrest testing were not readily identified as such in the title, making them difficult to access. Others were either in the “grey literature” category or were the subject of torturous international loans, but were obtained where possible.

Together with the library holdings of Safety Squared, the various types of information obtained from the searches were examined and a review was written which reports on the findings.

The characteristics between the different types of test surrogate were analysed and compared in regard to their relevance to drop testing, the type of test results they produce, what information can be derived, and the advantages, disadvantages and limitations of the type of test.

Various interrelated issues were examined. Typically, these included:

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Other subjects which are closely associated with the project were mentioned in the report where appropriate. This does not mean that a full exposition has been undertaken on these subjects, examples of which include:

- male and female gender issues
- whole human body impact tolerance to acceleration, jolt / jerk, duration of acceleration, direction of acceleration, and localised accelerations of parts of the body.

1.4 DEFINITIONS

For the purposes of this report the following definitions are used, together with the corresponding SI units of measurement:

1.4.1 Anthropomorphic

Resembling or having human form with human attributes; ascribing human characteristics to non-human things.

1.4.2 Anthropometry

Comparative study of sizes and proportions of the human body.

1.4.3 5th Percentile

Only 5% of measured values in a given population are smaller than the 5th percentile measurement.

1.4.4 50th Percentile

50% of measured values in a given population are smaller than the 50th percentile measurement and 50% are larger; the “mean or average value”.

1.4.5 95th Percentile

Only 5% of measured values in a given population are larger than the 95th percentile measurement.

1.4.6 Acceleration due to Gravity (g)

The natural acceleration of free fall due to gravity, equal to 9.81 m/s².

1.4.7 Acceleration

Rate of change of velocity with respect to time in metres per second squared (m/s²). Where acceleration is expressed in units of “g”, for example an acceleration of 5g, this corresponds to an acceleration of 5 times the acceleration due to gravity, that is 49.05 m/s².

1.4.8 Jolt (or Jerk)

Rate of change, or rate of onset of acceleration with respect to time in metres per second cubed (m/s³). Where jolt is expressed in units of “g/s”, for example a jolt of 500g/s, this corresponds to a jolt of 500 times the acceleration due to gravity per second, that is 4905 m/s³.
1.4.9 Body Centred Geometry System

The convention used to describe the direction of impact accelerations as shown in Figure 1 and Table 1.

![Figure 1: Body centred geometry system to describe the direction of impact accelerations](image)

**Table 1**

<table>
<thead>
<tr>
<th>Body centred convention</th>
<th>Acceleration descriptive</th>
<th>Vernacular descriptive*</th>
</tr>
</thead>
<tbody>
<tr>
<td>- $a_x$</td>
<td>Forward</td>
<td>Eyeballs in</td>
</tr>
<tr>
<td>+ $a_x$</td>
<td>Backward</td>
<td>Eyeballs out</td>
</tr>
<tr>
<td>- $a_z$</td>
<td>Upward</td>
<td>Eyeballs down</td>
</tr>
<tr>
<td>+ $a_z$</td>
<td>Downward</td>
<td>Eyeballs up</td>
</tr>
<tr>
<td>+ $a_y$</td>
<td>To Right</td>
<td>Eyeballs left</td>
</tr>
<tr>
<td>- $a_y$</td>
<td>To Left</td>
<td>Eyeballs right</td>
</tr>
</tbody>
</table>

*(eyeballs movement in inertial response to applied acceleration)
1.4.10 Bio-fidelity

The degree of transferability of the test surrogate’s response characteristics to that of the human body in identical test conditions.

1.4.11 Cadaver

A human corpse utilised as a surrogate in impact biomechanics research testing.

1.4.12 Kinematics

The study of the motion of bodies and containment systems without reference to mass or force.
2. DYNAMIC PERFORMANCE TESTING OF FALL-ARRESTING SYSTEMS

2.1 BASIC FALL-ARRESTING SYSTEM

A fall-arresting system (FAS), is a number of fall-arrest equipment components which are connected together in series to make a physical link between the worker and the workplace structure, Riches (1998b). In the most basic type (Figure 2), the components consist of:

- a full body safety harness, which is worn by the worker;
- a type of lifeline, which links the harness and the structure;
- connectors, which join the above components to each other and to the structure.

Once in the full body safety harness, and once all the connections are made to the structure, the worker and workplace structure in effect become integral parts of the FAS. Note that whilst a direct connection can be made between the lifeline connector and the workplace structure, often it is through intermediary equipment such as some form of localised, designated anchor device.

Figure 2: Basic FAS and component arrangement
If a fall occurs, the worker is arrested by virtue of being connected to the workplace structure, i.e., the structure provides a reaction force. Due to the downward motion of the fall, the lifeline becomes taut, and the sudden resistance caused by this causes the worker to decelerate abruptly, principally at a rate which is controlled by the energy absorbing qualities of the lifeline and its design.

Since the ability of the human body to withstand an abrupt rate of deceleration without injury is limited, it became essential to be able to test the response of a given FAS to a simulated fall, to ensure that recorded shock loadings were below the levels that were known to cause injury and, indeed, to prevent failure of the FAS itself, Steinberg (1977). It was also important to understand how a FAS might behave and extend under loading, and if there were any unsafe or undesirable aspects to its operation.

2.2 DROP-TESTING

Drop-testing became the term used to describe the technique of simulating an arrested fall by using a test surrogate for the human worker. Various test methods were developed, a great number of which have been documented in technical standards and research literature around the world, as in EN 364, (1992). In principle the methods all share the common feature of subjecting the FAS under test to a measured amount of kinetic energy. This is achieved by connecting a test surrogate into the system, and then dropping it so that it free falls over a prescribed distance before the FAS responds and brings it to a complete halt (Figure 3). Various measurements can be recorded for assessment, but the most basic requirements include the measurement of maximum arresting force and distance.

2.3 DROP-TESTING APPLICATIONS

Drop-testing may need to be employed at a number of points in the life cycle of a FAS, and this is one of the main reasons why a number of different types of test surrogate have evolved. These points include:

- research based testing to determine human impact tolerance levels and other injury producing criteria, not necessarily performed with FAS
- research and development testing on prototype FAS involving organisations such as manufacturers, test institutions, enforcing agencies, and users
- independent testing by test institutions to satisfy statutory or technical standard provisions
- specific in-situ testing to give assurance and satisfy customer demand
- batch testing as part of a manufacturer’s quality assurance scheme
- evaluation of competitor products by manufacturers, for market research reasons
- evaluation of available products on market place by user groups to differentiate the most appropriate and best performing types
- accident investigation testing involving accident simulation.
Stage 1:
The test surrogate is connected to the FAS and is freely suspended at height “A”.

Stage 2:
The test surrogate is raised to the pre-release position at height (A + B).

Stage 3:
The test surrogate is released and free falls over distance “B”. The FAS elongates and applies a reaction force, which is measured at the force measurement device. The test surrogate is stopped over an arrest or elongation distance (A – C). The total fall distance from release to the post-drop equilibrium position is (A + B – C).

Figure 3: Example of sequence of events in a drop test.
2.4 TEST SURROGATES

Apart from occasional experimental testing as reviewed in Section 3, human volunteers cannot be used for testing on an ongoing basis due to the risk of injury and for ethical reasons. Consequently, a variety of different test surrogates have been developed, which include:

- solid, rigid weights of regular shape (eg: Figure 4)
- sand bags of regular shape (eg: Figure 5)
- rigid quasi-human torso shape, without head and limbs (eg: Figure 6)
- full body anthropomorphic, articulated dummy, approximating to a human being (eg: Figure 7).

The use of the different types have reflected the level of expertise in each country at particular times, the type of testing under consideration, the influence of testing performed in allied industries, (eg: vehicle passenger restraint and aircraft ejection seat industries), the reasons behind the testing, testing philosophy, availability, expediency, and cost.
Figure 4: Example of test surrogate - solid, rigid weight of cylindrical shape

Figure 5: Example of test surrogate - sand bag of regular shape
Figure 6: Example of test surrogate – rigid quasi-human torso shape, without head and limbs

Figure 7: Example of test surrogate – full body anthropomorphic, articulated dummy, approximating to a human being
3. EXPERIMENTAL ASSESSMENT OF PROTECTIVE METHODS IN IMPACT SITUATIONS USING HUMAN VOLUNTEERS

3.1 IMPACT BIOMECHANICS

Impact biomechanics is that area of research which is focussed on the protection of personnel in impact situations. This covers fields such as:

- aircrew and passenger restraint systems offering protection in aircraft crashes
- ejection seats in military aircraft offering emergency evacuation in life threatening circumstances
- parachute deployment and subsequent retarded descent to the ground
- passenger restraint systems offering protection in vehicle crashes
- fall-arrest systems offering protection in falls from a height
- safety equipment offering protection in industrial and sporting activities.

Impact biomechanics mainly deals with applied loads or accelerations that have high jolt rates, King (1993), and with durations of less than one second, Glaister (1978), von Gierke and Brinkley (1975).

3.2 EXPERIMENTAL TESTING

Impact testing is necessary in order to simulate any of the circumstances as listed above in order to verify the degree of protection, and to detect any design deficiency or undesirability. However, if the impact test is likely to produce an environment in the potential human injury range, then it would not be reasonable or ethical to use human volunteers in that situation, King (1993). Accordingly, designs that provide optimum protection require the knowledge of impact response characteristics of the human body and hence the need to acquire human impact tolerance data.

Tests with human volunteers have therefore required that the imposed impact force or acceleration be increased gradually and that the tests be stopped either when the subject feels subjective discomfort or when the researcher feels that proceeding further would present a risk of injury to the test subject, Snyder et al (1977). Such tests have generally remained at the subjective injury level and well below that at which significant or non-reversible injury occurs.

Impact tolerance information has been obtained from several sources, including experimental tests with human volunteers, Scheubel (1950), with cadavers, Ruff (1950) and with animals, for example Gauer (1950) and Blake et al (1952). Also, for example, from investigation of vehicle crashes and accidents involving substantial falls from a height, de Haven (1942) and Turner (1919). This permits assessment of injuries in relation to impact dynamics. Particularly in the vehicle crash protection industry, this information is used in the design of anthropomorphic dummies, Foster et al (1977), which in turn are frequently used in studies which correlate dummy response to human injury.
Mathematical modelling can also utilise data from all of these sources in attempts to predict the consequences of impacts under a specific set of conditions, Snyder et al (1977).

A great deal of the literature surveyed suggests that impact tests using human volunteers have been conducted primarily by the military in the aerospace field. As a result, most of the data are for young adult male subjects. These studies are limited because they provide data for a relatively small segment of the general population, and because the impact forces must be kept below injury-producing levels. However despite observing test protocols, occasionally errors do occur and subjects are injured, as in Swearingen et al (1960). The effects on a male subject seated in a rigid chair subjected to a vertical drop at a reported maximum deceleration of 95g at a jolt of 19000g/s, producing 10g at shoulder level at a jolt of 600g/s, was compared with similar results in which internal abdominal injuries had been sustained. In another test, Beeding and Mosely (1960), a rear facing horizontal sled impact exceeded the test protocol limit substantially, reaching a deceleration of 83g for 0.04s at a jolt of 3826g/s measured at the chest level, (transverse to the spine), and produced what would have been irreversible shock, if medical expertise had not been readily available. There is also a case of injury in human fall-arrest tests as recorded in Amphoux (1982). In this, drop tests were first conducted on an anthropomorphic dummy wearing a type of chest harness, as a precaution to ensure that subsequent tests with human volunteers would not be injurious. A chest harness consists of a horizontal strap of material worn at waist level like a belt, with two straps attached which run up the back of the body, over each shoulder, and then back down the front of the body, and are attached again to the belt strap but at the front. Drop tests were conducted on human volunteers with free falls of between 0.5 and 0.6 m with no untoward results, until when, in identical fall conditions, two rib fractures occurred.

3.2.1 Parachute Opening Simulations

Nevertheless the studies in clause 3.2 do provide important insights and implications for fall-arrest designers. For instance in Beeton et al (1968), parachute opening snatch simulations were performed on three individuals whose mass with equipment ranged from 98.4 to 112 kg. When a crewman elects to activate the ejection seat in a stricken aircraft, after the subsequent ejection there is a point in the process where the crewman and seat separate, and the snatch loads referred to above occur when the crewman’s parachute deploys. The simulations were achieved by drop-testing with individuals wearing a parachute harness, with the riser straps emanating from the shoulders and connected to a test structure. Each riser strap contained a strain gauge link to measure decelerative loads. The subjects were raised to a pre-determined height, and after warning were released so that they fell and were decelerated by the riser straps. Seven tests were conducted and maximum deceleration varied from between 5 to 12g, corresponding to decelerative forces of between 4.9 and 13.2 kN according to the subject’s mass.

These tests did not just focus on shock loadings but also on how the harness reacted in relation to the body. A number of important observations were made. First, during the tests the subjects did not report any particular discomfort except in Test 5, where the cross chest straps of the harness rode up into the armpits causing some pain. This was as a result of an incorrectly adjusted harness rather than a design deficiency, because after correct adjustment and with subsequent test runs with the same subject the matter did not reoccur. Second, a number of components mounted on the harness, necessary to crewmen upon ejection from modern combat aircraft, showed no sign of riding up with the stretch of the harness and interfering with important regions of the body. Third, it was noted on some test runs that some head-whip occurred. In simple terms this phenomenon is due to the inertial lag of the head in respect of the main torso part of the body receiving offset acceleration, due to the hinge-like nature of the neck. However the head-whip was determined to be as a result of test method error, in the way that the head was held in relation to the suspension sling before dropping took place.
3.2.2 Body Containment

A further series of tests in Beeton et al (1968) analysed the containment and restraint aspects of a parachute harness, by way of human test subjects being strapped into a proposed ejection seat and being exposed to high levels of deceleration in the fore and aft plane. Deceleration was produced by swinging the subject and seat suspended from the laboratory roof, and arresting the swing at the bottom of its trajectory by cables, much in the same way as reported in Ruff (1950).

A total of 48 human exposures to deceleration were undertaken, in the fore and aft plane. Peak deceleration ranged from 3.5 to 16g at jolts of between 47 and 260 g/s. An interesting aspect in these tests is the selection of subjects whose sizes ranged to both extremes of the anthropometric distribution of aircrew size. The three measurements given were: stature height (total height when standing erect), sitting height, and weight. What is noticeable, is that a test subject with a 97th percentile stature height and 92nd percentile sitting height only had a 74th percentile weight, and that another test subject had a 65th percentile stature height and 60th percentile sitting height, but had the largest percentile weight in the pool of subjects at the 90th percentile.

What this confirms is the well known fact that human beings are all different to each other in terms of their proportions and comparative dimensions. Just because a person has a 95th percentile stature height, it does not follow that they will also have a 95th percentile waist measurement and a 95th percentile weight. Each body dimension will probably be at a different percentile position, and this is why it is important to state, when “something is 60th percentile”, what dimension is being referred to. To say simply that: “this person is 60th percentile” does not convey anything; one has to refer to the measurement under consideration. Anthropometrics has important ramifications in the design of test surrogates, as discussed later.

A further problem which arises with this matter is that, when human geometry can affect the outcome of a test, it is important to ensure that a number of tests with a large enough permutation of human sizes is utilised, of those dimensions which are critical to the test. Otherwise it may be possible that the system under test may not be tested with a certain size of human being, which could lead to the system not working properly for that size. This is one of the main problems in testing with humans, because there is such a variety in shapes and sizes. It is interesting to note that, in the testing cited, there were particular containment problems with the harness that were only detectable with certain sizes of test subject.

3.2.3 Industrial Fall-Arrest Simulations

Similarly, in Reader et al (1969), a number of human drop-tests were performed in order to assess various industrial fall-arrest harnesses at that time, for use by aircraft servicing personnel. Concerning the range of anthropometric sizes, it is interesting to note that one test subject had a 70th percentile stature height and 60th percentile sitting height, but only a 25th percentile weight and a 2nd percentile waist! At the other end of the scale another test subject had corresponding percentile measurements of 50th, 75th, 98th and 99th respectively.

Each of the harnesses was initially subjected to a suspension trial, consisting of slowly lifting and suspending the test subject whilst in the harness. Those harnesses which were uncomfortable on suspension, or with which there was probability of injury, severe discomfort or pain, were not assessed at high levels of vertical acceleration.
Four test subjects wearing each type of harness in turn were connected to a test structure via a load measuring device by a 3.05 m long steel cable and were dropped in order to simulate the vertical acceleration caused by the arrest of a free fall. The dropping distance was progressively increased to 0.6 m to produce similar decelerations to those exhibited by inertia locking devices used at the time.

The maximum deceleration recorded was 4.8g corresponding to a decelerative force of 4.27 kN measured in the cable over 32 drop tests, 13 tests with human subjects and 19 with an anthropomorphic dummy. Note that the documentation does not give the reason for the use of dummies, although this may have been to do with tests on waist belts as mentioned in the paragraphs below. The attachment points (where the steel cable was connected to the harness) were either in the dorsal or sternal positions, depending on the design.

Whereas Reader et al (1969) concluded that vertical accelerations slightly under 5g at free falls of 0.6m were tolerable by the test subjects, without apparent injury, the report also mentions that some features of the harnesses in question were potentially quite dangerous. This underlines that impact testing should not just assess dynamics – i.e. levels of acceleration and force – it should also assess kinematics – how the body and containment device react and move in response to an arrest. This is emphasised in other human acceleration research fields where body containment is essential, as in Jackson and Ward (1997). It is asserted that the evaluation of dynamics is only one part of the assessment of human containment systems that undergo acceleration. Ergonomics also plays a vital part if the design is to be effective in ensuring human safety.

In Reader et al (1969), during one of the suspension tests, the chest straps of the harness became very tight and lifted towards the face, and the back straps came in contact with the back of the head. No drop tests were conducted with this harness. In the case of another harness, again in a suspension test, riser straps emanating from the shoulder straps of the harness, chafed the ears of the test subject and struck the head, if the head was not held centrally. This harness was assessed as being potentially dangerous, as it could cause serious head and neck injuries, especially during a tumbling fall. In the case of another two types of harness which were drop-tested (types that had passed the suspension tests) the harness straps struck and chafed the back of the neck, which could only be avoided by flexing the head forward. These types of strap induced injuries are described in Figures 13 – 16.

Three types of waist belt for fall-arrest purposes were also assessed in Reader et al (1969). A waist belt is simply a band of material that encircles the body at waist level. Suspension in the waist belt caused pain, both in the prone or supine positions, as the body tended to fold around the belt. It was judged that at high vertical accelerations the belts could either rise uncomfortably high around the chest, or, if the subject was in an inverted fall position, slip off the body altogether. The waist belt would also allow the body to pivot about the belt and suspension cable allowing the head to strike adjacent structures. Finally, it was judged that the forces imposed by a waist belt on the body during the arrest of a fall could cause serious visceral injuries and, in conjunction with the other findings, the report did not recommend waist belts for fall-arrest use. This was confirmed again in Reader (1979), in which a number of helicopter crashes were reported. During one particular crash, a crewman was restrained by a waist belt and suffered a fractured spine which, according to the medical staff who investigated the accident, was caused by a jackknifing-folding action of the body around the belt.

It should be noted that in Reader et al (1969) all of the drop tests were conducted with the subjects in a vertical upright situation, i.e. “feet first trajectory” in the drop. In Rushworth et al (1986), where a series of ergonomic-based tests were conducted on a range of fall-arrest harnesses, this single orientation of drop-testing was seen as of limited value, and emphasised Steinburg (1977) by quoting: “body orientation in a fall is highly variable and it will almost certainly undergo twisting, tumbling, flailing and jackknifing”.

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It was also claimed by Rushworth et al (1986) that little evidence was available regarding arrest forces developed in such realistic fall situations. It was therefore judged that human subjects could not be used in such realistic fall conditions due to the likely risk of injuring a person, and so an anthropomorphic, articulated dummy was used to simulate toppling sideways and backwards in that particular drop-testing project.

In Rushworth et al (1986), slow lifting and suspension tests were carried out in a similar fashion as reported in Reader et al (1969). Of significant note is that four of the harnesses showed dangerous tendencies for the shoulder straps to apply pressure to the neck region. Basically, the inner edges of the converging shoulder straps were pressing into the sides of the neck, and the problem was exacerbated for larger subjects. In one case, the subject almost lost consciousness and the trial had to be terminated quickly, in order to remove the direct pressure of a strap on the subject’s carotid artery. These tests therefore showed up design deficiencies that other test methods hitherto had not. In a further report describing aids in fall-arrest harness selection, Rushworth and Mason (1987), it was recommended that before final selection of a harness takes place, some form of a suspension test should be carried out which involves the intended user.

It was mentioned in this report that shoulder straps of fall-arrest harnesses have a tendency to pull away from the body and that, when dorsal harness attachment points are utilised, these straps can move and press against the side of the neck to the extent of restricting blood circulation. Clearly, harnesses with these deficiencies should be avoided.

### 3.2.4 Induced Localised Acceleration in Human and Dummy Based Drop-Tests

In more recent research, Mattern and Reibold (1994), a project was undertaken for the purposes of optimising the design of FAS. The project was concerned with gaining knowledge of the biomechanical stresses on the human body during the fall-arrest deceleration process in order to ascertain the risk of injury, and to be able to evaluate the effectiveness of designs in preventing injury.

It was stated that biomechanical loads in the injury-free range can be obtained by using human test subjects, but for higher loads a model would required, and in this case a 50th percentile Hybrid II dummy was utilised, (stature height and weight), as used in vehicle safety research. Bio-fidelity of the dummy, (the transferability of the load parameters from the dummy to the human body), was checked by comparison with human test subjects in analogous fall trials using identical measuring equipment.

A total of 24 fall trials with human subjects were carried out, equipped with a full body harness and connected to the test structure via a dorsal-attached energy-absorbing lanyard, rated with a maximum arrest force limitation of 5 kN. Free fall heights ranged from 0.25 to 1.5 m, in the feet first direction. A total of 30 analogous trials were carried out with the Hybrid II dummy, with free fall heights ranging from 0.25 to 4.0 m.

Human test values that were considered biomechanically significant were recorded as follows, with corresponding Hybrid II dummy values in brackets. These values are all maximums:

- translational head acceleration: \( \leq 10 \text{g} \) \( \leq 13 \text{g} \)
- angular head acceleration \( \leq 530 \text{rad/s}^2 \) \( \leq 500 \text{rad/s}^2 \)
- translational acceleration on torso \( \leq 12 \text{g} \) \( \leq 13 \text{g} \)
All the values were compared with and were reported to have been well below the protection
criteria applicable in vehicle safety research, but a number of researchers in the fall-arrest field
would probably argue that vehicle protection criteria are not applicable to fall-arrest
circumstances, and that parachute opening criteria are more relevant. For instance in von Gierke
and Brinkley (1975), it is mentioned that one major difficulty in determining useful impact
exposure-limit criteria is that impact levels are not determined by the biology of the human
alone, but are strongly influenced by, and are coupled to, the body support or restraining system
used in applying the force to the subject. A definition of impact-exposure limits without
definition and accurate description of the support and restraint system is meaningless.

It would also appear from the available literature that most of the knowledge in regard to human
tolerance to fall-arrest deceleration is based on previous aerospace research and not vehicle
impact protection research. This is mainly due to the fact that human tolerance to acceleration
depends in which direction it is applied to the body, and as mentioned in von Gierke and
Brinkley (1975), on the restraint system in use. In vehicle research, accelerations are typically
applied in the $a_x$ plane, and more lately, in the $a_y$ plane, but with the occupant restrained in a
seat, (see Figure 1 for convention). In fall-arrest situations, accelerations can be initially applied
from any direction, and are subsequently applied in the $a_z$ plane, once the body has swung in
alignment with the FAS. The restraint afforded by the full body harness is quite different to that
afforded by a vehicle passenger seat, and lap-and-shoulder belt.

Ejection seat and parachute opening shock accelerations are mainly applied in the $a_z$ plane,
where tolerance is relatively high, whereas vehicle passenger restraint accelerations are applied
to the $a_x$ and $a_y$ planes, where tolerance may be 25% lower, Steinberg (1977). This does not
mean of course that even the best aerospace data is completely relevant to the establishment of
tolerance limits for fall-arrest deceleration, since such data is limited to young healthy male
volunteers, restrained in an optimal position and anticipating the impact. These are not
circumstances which are present in arrested falls. For instance the Martin Baker company’s
acceleration tolerance criteria, Lilley (1996), for ejection seat operation, (human limits under
which no injury will occur), are:

- maximum acceleration not to exceed 21g
- maximum duration of 0.1 second at an acceleration of 21g
- rate of rise of acceleration not to exceed 300g/s
- that in sustaining these accelerations the body must be restrained so that adjacent spinal
  vertebrae are square to each other.

Clearly, these criteria could not be used to estimate tolerances for fall-arrest situations since the
containment system cannot keep the spinal column upright. Therefore, utilisation of data from
other impact biomechanics fields for fall-arrest purposes must be carried out with extreme
cautions.

One important point about the use of vehicle occupant protection criteria however, is that the
impact exposure limits are in terms of “probabilities of injury” and/or fatality, instead of the
perhaps oversimplified concept of a “single tolerance limit” which is currently used in fall-arrest
technology.
In terms of kinematics, there are similar findings in Mattern and Reibold (1994), as reported elsewhere, e.g. Reader et al (1969). First, it was noted that in suspension, subsequent to the drop test, there was restricted movement in the neck area, because the harness shoulder straps had extended away from the body. Combined with this, the strap collecting plate at the back of the harness—a device which permits the shoulder straps to cross over at 90° before running down to the waist area—was dragged very close to the neck and back of the head. Figure 13 shows this possibility.

The medical viewpoint reported was to the effect that possible injuries due to forceful impact of the collecting plate against the neck or head could not be ruled out.

What is concluded in Mattern and Reibold (1994) is that more research was required, especially concentrating on different fall geometries, (testing the most unfavourable fall position in combination with the most unfavourable FAS). Need was also expressed to test different types of harness at different attachment points on the harness, and with a range of individuals with different anthropometry.

Further research as reported in Kloss (1998) utilised a Hybrid III anthropomorphic articulated test dummy, and conducted drop-tests from the head-first, prone and supine pre-release body attitudes. Accelerometers were fitted in similar anatomical positions to those reported in Mattern and Reibold (1994). Free-fall in the tests was 4 m using an energy-absorbing lanyard for the fall-arrest connection. Maximum decelerations were recorded at 25g for the head, 20g for the chest, and 15g for the pelvic region, (no directions stated). Again, these figures were compared with, and were reported to have been well below, the protection criteria applicable in vehicle safety research but, for the reasons outlined above, it is questionable whether deceleration criteria in the \(a_x\) plane with the occupant restrained in a seat are applicable to fall-arrest scenarios.

### 3.2.5 Other Drop-Testing Used to Establish Human Impact Tolerance

As reported in Hearon and Brinkley (1984), the French conducted limited fall-arrest testing with human beings in the 1970s, the purpose of which was to determine the maximum fall arrest force subjectively tolerable to human beings. Approximately 30 drop tests were conducted, with a maximum arrest force of 4.8 kN recorded over a fall distance of 0.8 m at a maximum deceleration of 7g. The volunteers wore chest harnesses and it is in this series of test that the rib fractures occurred as reported above in Amphoux (1982). The French concluded that the maximum arrest force, rather than the fall height, was the critical factor in determining human tolerance to fall-arrest.

In Ulysse and Sulowski (1982), Ulysse records a drop conducted on a human volunteer whilst wearing a full body harness connected to the test structure via a 2 m long energy absorbing lanyard, (11 mm diameter mountaineering rope with tear-ply type shock absorber), attached to the dorsal position. The subject’s mass was 88 kg with equipment. The free fall was 2 m, which generated 3.8 kN in the lanyard. Some accelerometers were also mounted on the subject’s head and chest, but the readings are difficult to interpret.

In Amphoux (1982), a series of anthropomorphic dummy based drop tests is discussed in which a maximum arrest force of 12 kN was recorded at the anchor point. This figure was compared with parachute opening research which was not cited, in which it was found that 12 kN was an upper limit of tolerance.
Whilst it can be determined from the accounts of Amphoux (1982 and 1983) that significant reference has been made to the parachute research work in Teyssandier (1967) and in Teyssandier and Delahaye (1967), these accounts do not refer to an upper limit of tolerance, except the mentioning of the crushing resistance of three lumbar vertebrae as being 5.89 - 7.85 kN, but in the context of the shock experienced by a parachutist on landing, i.e. forces being transmitted up the legs.

In Teyssandier (1967) the work does confirm that a typical French military parachute (the T.A.P. 600), does create an opening shock force of about 2.2 kN, due to more efficient parachute folding techniques, confirming statements in Amphoux (1982), but Teyssandier (1967) goes on to say that this is for a person of 75 kg mass. Also it is clear from Teyssandier and Delahaye (1967) that French military regulations at the time limited the mass of parachutists to 80 kg. This would have to be accounted for in any attempt to utilise parachute research data to develop fall-arrest tolerance thresholds, where a falling mass of 100 kg is the normal consideration.

The parachute opening shock force of 2.2 kN is very low, even for a falling mass of 75 kg, especially where other research has shown higher figures, e.g. as in Reid et al (1971) (see below), who is referred to in Amphoux (1983). However when the information is scrutinised, it can be seen that these types of parachute are automatically opened by a rigging line in an aircraft’s cabin upon the parachutist’s exit. Consequently there is little free fall, and the aircraft is not likely to be at a high altitude (i.e. military parachutists will want the minimum of descent times), both factors that affect parachute opening shock forces, Reader (1970).

After discussing and emphasising the differences between falling and parachuting, it was concluded in Amphoux (1982) that it would be reasonable to half the upper tolerance limit of 12 kN to 6 kN as that acceptable for fall-arrest circumstances. This approach was also based on the crushing resistance of the spinal column, as most relevant in a feet-first trajectory fall. This was the limit accepted in the French technical standard for fall-arrest equipment, NF S 71-020 (1978), and has been accepted for modern-day European and International standards, e.g. EN 353-1 (1992) and ISO 10333-3 (2000), but it should be noted that these standards are based on a falling mass of 100 kg. In the American standard ANSI Z359.1 (1992) the French halving of the 12 kN figure to 6 kN was seen as arbitrary, and a limit of 8 kN was set, probably reflecting Canadian influence, see section 4.2 in this report.

[Author’s note: In Scheubel (1950), German wartime aviation research showed that parachute opening shock could induce a total of 10.25 kN on the parachutist’s body, via two shoulder riser straps, subject to descent velocity, altitude, canopy size, and parachutist’s mass. Force-time curves show the maximum force to be approximately 4.91 kN in the right riser strap, and 5.3 kN in the left riser strap, occurring simultaneously at time = 1.56 s after the test started, and are shown to summate to 10.25 kN at the same 1.56 s point. Similarly in Reid et al (1971), average parachute opening shock was recorded as 7.3 kN, (3.65 kN per shoulder riser strap), with the highest results from a U.S. Navy parachute, recording 10.6 kN total riser opening force. In ejection seat research, Ruff (1950), German wartime medical expertise demonstrated that 18 to 23g was the maximum acceleration range tolerable for a human of 75 kg mass in the az plane, provided that the duration of that acceleration was between 5 and 500 ms. This limit range was imposed by tolerance to crushing of individual elements of the spinal column. This limit range has a force equivalent of between 13.25 and 16.9 kN.]
However other injury producing mechanisms such as acceleration and jolt durations, and levels of jolt, which were discussed in Amphoux (1982), have not had limits set in standardisation documents, probably due to complexity of measurement. Amphoux (1982) insists that acceleration data alone is not enough to assess the risk of injury, and that jolts of around 10000 m/s³ had been recorded at the head in head-first fall trajectories using anthropomorphic manikins. Stapp, a well renowned researcher in the field of collision injury dynamics, for example see Stapp (1966), is quoted for comparative purposes, and the opinion is put forward that such levels may be particularly threatening to the cervical column of the subject, (neck part of spine). In a later paper, Amphoux (1983), it is admitted that the dummy’s neck was “not a perfect model of cervical articulations”, such that measurements on the dummy may not accurately reflect the order of acceleration in a human being. Nevertheless, reduction of jolt is seen as a topic for further research.

The only partial exception to the standardisation case above occurs in Military Specification MIL-H-24460A(SH) (1981), in which the maximum allowable arrest force experienced by a falling person during arrest was set as 3.115 kN, (700 Imperial pounds weight), plus an allowable one-time excursion to 5.34 kN, (1200 Imperial pounds weight), providing that the elapsed time when the force is above 3.115 kN would not exceed 100 ms. In this document harness and lanyard of length 1.83 m are tested together with a “simulated human torso” of 96.2 ± 1.36 kg, which is allowed to free fall 1.83 m. No detailed specification for the torso is given.

Kinematics is also given a strong mention in Amphoux (1983) in which it is emphasised that the position of harness buckles, seams and straps must never threaten any organ in a fall-arrest situation. It is also mentioned that in fall-arrest impacts, harness straps are stretched, displaced and twisted, and that this change in shape of the harness must not strangle the worker.

Some animal experiments are recorded in the literature, particularly in Blake et al (1952). In this, two phases of drop-test experiments were conducted on dogs wearing waist belts and lanyards connected to a steel cable. The cable was routed over a pulley system and was attached to a test mass. The mass was raised and allowed to free fall over a set distance, the effects of which were transmitted to the animal. There are detailed medical descriptions of the condition of the animals after the tests.

In the first phase of experiments the test mass is not reported, nor is there an account of the arrest loads generated in the cable. There is also no explanation why some animals received multiple exposures to loading, and there is no account of the number of dogs used in the second phase. The main problem generated with this kind of information is how it can it be applied to human beings. Animals are in many ways similar to humans, but the extrapolation of injury and tolerance data from animals to humans has been a subject of controversy in the past, Snyder et al (1977).

Nevertheless, Blake et al (1952) concluded that a force of 17.8 kN, (4000 imperial pounds weight), would almost certainly result in injury to humans, so that fall-arresting force as applied to humans should be limited to half that value, ie 8.9 kN (2000 imperial pounds weight). This criterion, in conjunction with results from aerospace and vehicle crash restraint work was accepted by Symmons (1973) and by Dickie (1975), in Canadian test evaluations of FAS.
Since impact tests which produce significant injury cannot be conducted on human volunteers, a number of researchers have used human cadavers for this purpose, especially in the vehicle crash protection industry, King (1993). Whilst it is admitted that the main deficiency with using this method is the lack of muscular response and tone, (a similar criticism of anthropomorphic, articulated dummies), the brevity of the impact duration renders muscular response virtually irrelevant in terms of its ability to modify body kinematics. Muscle tone can be simulated by applying clamping and support devices. However there is also the problem of large variations amongst subjects, impracticality of use in test laboratories and limited availability to consider. Consequently one of the main uses of cadavers has been to develop realistic anthropomorphic test dummies, such as the Hybrid III model, Foster et al (1977), which has been used in other applications, e.g. as in Hulme and Mills (1996), and Edwards and Neale (2000).
4. ASSESSMENT OF PROTECTIVE METHODS IN IMPACT SITUATIONS USING TEST SURROGATES

4.1 TESTING

As demonstrated in Section 3, the use of human beings for experimental and research-based testing has a number of limitations, in particular where realistic fall situations need to be studied. As argued in Rushworth et al (1986), and in Mattern and Reibold (1994), where headfirst, pivoting or tumbling falls need to be analysed, there is little evidence available in regard to human injury thresholds, and so realistic models are needed to substitute for human beings. Consequently in a number of the previous research projects cited, anthropomorphic, articulated test dummies of various descriptions were utilised.

However not all testing is research-based, as described in Section 2.3. There are other types of test which are much simpler in comparison, and assess more basic criteria, and so other types of test surrogate may be more justified. For example, if testing a prototype FAS for the first time, it might be appropriate to conduct a simple test using a rigid weight, to make sure that the FAS was capable of performing the basic function of arrest. If it was incapable of doing this it would be a waste of time and expenditure to conduct this in a more complicated fashion.

The choice as to which type of test surrogate to use in a test may have already been made on behalf of the FAS designer or test engineer, whether simple weights or sandbags or dummies, for instance by legislative or by technical standard based provision, eg: EN 364 (1992). But there are many other cases where the designer or engineer can choose. The choice is important, and is based on what circumstances the test is attempting to recreate, what degree of representation for the human being is required, and what types of parameter are being measured. Obviously expediency, surrogate availability and cost enter into the decision making process.

As with the range of fall-arrest drop test surrogates as described in Section 2.4, there are also a range in other impact biomechanics based industries. In assessing parachute-opening shock forces in the parachute industry, Reid et al (1971), Scheubel (1950) and Military Standard MIL-STD-858 (1969), cite a range of test surrogates, particularly the rigid-quasi human torso shape, without head and limbs, and the full body anthropomorphic articulated type, approximating to a human being. Similarly, in Armstrong and Waters (1969), a whole range of surrogates, including the torso type, the sand bag type (although more human in shape than that shown in Figure 5, having readily discernable limbs and head) and a range of full body articulating types are described in a programme to assess vehicle crash protection criteria. So it should not be surprising to see a similar range of test surrogates in the fall-arrest field, Sulowski and Brinkley (1988).

What must be recognised, however, is that each type of test surrogate attempts to be a substitute for the human being in various degrees of sophistication, and therefore the person responsible for interpreting the test results that use a particular surrogate must be aware of the limitations imposed by that degree of sophistication. For instance, a solid rigid weight used in a drop test can only simulate the total weight attribute of a human being, it cannot simulate any other human attribute. Also, the whole act of substitution raises the important question of bio-fidelity, that of understanding how the results of surrogate testing compare with the results of identical tests if they had been performed with a human being. Mattern and Reibold (1994), describe this as the “transferability” of parameters from the surrogate to the human body.
4.1.1 Where Choice of Surrogate Affects Ability to Arrest

A prominent series of tests, carried out in the UK in the mid-eighties, served to emphasise the importance in justifying the choice of test surrogate based on the reason for or purpose of the test. A summary of the tests are reported in Clark (1985). The tests showed that although a particular FAS met the applicable technical standard of the time, BS 5062 (1973), it could under certain climbing conditions fail to arrest the fall of a person.

The type of FAS in question as described in Clark (1985) was of the vertical rail-based type, as described in EN 353-1 (1992), and shown in Figure 8. The rail part of this type of FAS is typically attached to a ladder run, which itself is permanently-installed to a tower or mast, and provides a vertical access route. A trolley device, which is connected to a worker’s safety harness via a short connecting lanyard, is slid onto the rail, and is free to slide up and down the rail in response to climbing movements, but will lock onto the rail in response to a fall. At such time, the trolley then effectively resists the downward motion of the worker, whose fall is arrested.

![Figure 8: Example of a vertical rail-based FAS](image-url)
Clark (1985), describes the fact that although the FAS met the then current standard, BS 5062 (1973), this was only a confirmation of its strength and durability attributes. The tests contained within the standard did not, in Clark’s view, show how the FAS would perform in actual “man-fall conditions”. This may have been prompted by one of the design requirements of the standard, to partially quote clause 3.2: “All devices shall be so designed so that when used correctly they will arrest a falling human body”. This requirement was tested for in the standard by attaching a lanyard of 1 m length to the trolley and to a rigid test weight of 136 kg mass. The test weight was then raised above the trolley to the extent of the lanyard, and then released. The test weight would then fall freely through a distance of 2 m, that is twice the lanyard length, before being arrested. This in fact was a very onerous overload test, which can be seen from the design requirements clause 3.3, which states: “the length of any safety line, (the line which connected trolley to worker’s harness), shall not exceed 40 cm”. In such realistic fall circumstances, the actual free fall possible from such a length would be a maximum of 0.8 m (twice lanyard length). So in terms of free fall, the drop test was in actual fact an overload test with an overload factor of 2.5 (2 ÷ 0.8), and therefore a test for dynamic strength rather than fall arrest capability. Another clue to this is that the drop test had no requirement to measure arrest force, being typical of other vertical rail-based fall-arrest standards of the time.

As a result, Clark (1985) makes the statement that testing under “man-fall conditions” was considered to be a fundamental requirement that ought to be included in approval procedures. It was realised however, that even though precise simulation was important, for safety reasons a human being could not be used. Clark asserts that the next best thing to a human being was used, namely an anthropometric dummy - a full body dummy, with fully articulating joints and limbs with the weight distribution closely resembling that of an “average man”. No definition of this is offered, and no mention is made of the manufacturer of the dummy or its specification. What is known is that the dummy was clothed and equipped with the normal rigger gear: helmet, boots, clothing and a full body harness, with a combined mass of 76 kg. Concerning this figure, and allowing 5 kg for the clothing and equipment, this would mean that the net weight of the dummy was approximately 71 kg, which, according to anthropometry tables, Bolton et al (1971), corresponds to the 40th percentile weight, not necessarily the “average man”, or 50th percentile value, which is 75 kg.

The FAS was installed onto a “Mast No. 1A”, a triangular section lattice steel mast of 57 m overall height. The test staff considered various situations in which a fall was likely to result, as opposed to a temporary loss of control or stability which could be recoverable. They concluded that a fall was most likely to occur when a loss of grip from both hands occurred in a non-recoverable manner, with the body falling away from the ladder. The loss of contact by one or both feet was thought unlikely to result in a non-recoverable situation, provided that one or both hands retained a grip, (likened to a slip from a ladder rung).

In preparation for the drop tests, and having been connected into the FAS and being suspended from a quick release device, the dummy’s hands were loosely taped to the mast and one or both feet were located on the mast’s built-in steps. Each drop test was recorded on high speed film running at eight times normal speed.

In two of the drop tests, the FAS failed to arrest the dummy, which collided with the ground in an inverted fashion. Figures 9a, 9b and 9c show the results of one such test, depicted by three consecutive snapshots in time from the high speed film footage.
Figure 9a, 9b and 9c: three consecutive stills from high speed footage showing drop test on vertical rail-based FAS, Clark (1985)
One of the main problems with conducting drop testing is that the duration of the test is extremely short, in the order of less than one second. By using unaided vision, it is very difficult to discern what is actually happening during a test, and so one method of recording such a high speed event is to utilise high speed photography techniques. This allows subsequent study of the event by playing the film back at a much slower speed. Examination of the high speed film pertaining to these specific drop tests enabled the reasons for the inversion of the dummy to be identified.

In Figure 9a the dummy is in the pre-release position. The hands are loosely taped to the mast and the left foot is resting on a step, simulating a climbing position. Clark (1985) does not specify the length of the lanyard connected between the trolley and the harness, nor is the position of the attachment point specified on the harness. But upon careful examination of the high speed film footage, and perhaps discernable in Figures 9b and 9c, it can be seen that the length of the connecting lanyard is approximately 1 m, similar to the test lanyard specified in BS 5062 (1973), and it is attached to the dorsal point on the harness, between the shoulder blades. Also from Figure 9a the dummy is positioned so that the dorsal point is likely to free fall through a distance of twice the lanyard length.

In Figure 9b the quick release device is activated to commence the simulated fall, the hands of the dummy fall free of the mast, and the body pivots outwards, simulating the non-recoverable fall situation.

In Figure 9c the situation becomes serious. The length of the connecting lanyard, its position of attachment on the body and the pivoting action of the dummy, all serve to apply a horizontal component of tension in the lanyard, and hence to the trolley. This prevents activation of the trolley’s locking mechanism or, having initially locked onto the rail, is subsequently caused to release, permitting the fall of the dummy to go un-arrested. In Figure 9c the degree of horizontal force being applied to the lanyard can be discerned by the slight bend seen in the rail, where it is coincidental with the trolley.

In analysing this case, in the first instance it could be asserted that the tests in question were invalid. This is because:

- the length of the lanyard used was approximately 1 m
- the free fall element of the drop test was set to be in the region of 2 m
- the dorsal attachment point on the harness was used.

What was simulated here was the overload test of BS 5062 (1973), but with “man-fall conditions”. This is counter-productive, since both types of test are conducted under different conditions, and seek to prove different aspects of design. Overload and actual use cannot be combined in one test, since there is an inferred safety factor in the overload test. In any case, the maximum length of lanyard permitted in “man-fall conditions” was 40 cm, as stated in BS 5062 (1973), so this is the maximum length that should have been used, or even shorter, as the length would have been controlled by the manufacturer of the particular FAS. Another point is that the FAS design was not compatible with the use of the dorsal attachment point on the harness, so this point should not have been used. Perhaps it was used because fall-arrest research asserted that it is a safer point to be attached to in an arrest, Amphoux (1982), as opposed to the sternal attachment point, which can be used on the front of a harness, and indeed, was specified for ergonomic reasons by the manufacturer of the FAS in question.
However, what these tests did show is that:

- when seemingly compatible pieces of fall-arrest equipment were connected together to form a FAS;
- when seemingly acceptable harness attachment points were utilised;
- where testing was performed under realistic fall situations by using a realistic substitute for a human being;
- where such a substitute was positioned on a realistic structure in a realistic pre-fall pose;

then it was possible to demonstrate that the trajectory of the simulated fall, and the geometry of the human being and workplace could interact with each other in such a way as not to permit the arresting of the fall. By using standard-testing methods of the time, which utilised a regular shaped test weight, this major deficiency had gone undetected. After all, such standards-based testing was concerned solely with the strength and durability attributes of the FAS.

The other point to note is that the test set-up with both hands taped loosely to the structure and with one foot resting on a foothold was repeatable and the test outcome was reproducible.

Clark (1985) reports a number of further actions that occurred as a result of the tests:

- modifications were introduced to the FAS including the shortening of the connecting lanyard to a maximum length of 260 mm and presumably with the connection made at the front attachment point, since this is not referred to; these changes were subsequently re-tested and produced satisfactory arresting results;
- the results and the high speed film were shown to the British Standards Committee responsible for the writing of BS 5062 (1973), and it was agreed to amend the standard to include performance testing using an anthropometric dummy, BS 5062 (1985);
- the results and the high speed film were shown to the International Standards Organisation Committee responsible for the writing of fall arrest standards, and a resolution was passed, again to include performance testing using an anthropometric dummy.

When reviewing BS 5062 (1985), such performance tests were introduced, but which also had deceleration forces imposed, namely 5 kN where the containment device was a waist belt, and 8 kN where it was a full harness. This was based on “an articulated, anthropometric dummy of 100 kg mass”; no further specification is given, except requirements in other parts of the standard show that at least the knee and ankle joints had to be lockable by some means.

There is also another test mentioned, the “system operational test” the purpose of which is to simulate the backwards fall from a ladder. In this test the requirement for the joint-locking of the dummy’s legs appears – the need to lock the joints in the legs to keep them straight, and to keep the feet at right-angles to the legs – as a factor contributing to test repeatability, as in some other impact related standards. This allowed the dummy’s feet to rest on a step so that upon release the dummy would pivot away from the test structure, before falling downwards, ie a degree of horizontal motion would be introduced.

Perhaps a more important factor was the point that these tests had to performed on full FAS and not individual components or partial systems. The trolley device together with its “anchorage line”, “matching connector” and “matching harness or belt” were tested together and as such were certified together under the then British Standards Institution “Kitemark” scheme. The certification license pertained to a complete FAS.
The whole concept of full FAS testing and certification, and the reasons behind this, are given
due emphasis in the Part 2 of BS 5062 (1985), which concerned recommendations for selection,
care and use. The relevant paragraph is quoted thus:

“Purchasers or users should not make any alterations to any part of the safety system as
originally recommended and supplied. It is important to ensure that the device/anchorage line
combination is in accordance with the marking on the device and with the marking on the
anchorage line. If it necessary to use any other combination, purchasers and users should be
aware that, in cases where equipment is constructed by the assembly of separate components,
even though the separate components may have formed part of a system that had previously
been tested and approved accordingly, the new equipment should be tested afresh. Thus it is the
responsibility of the purchaser to ensure that any new combination complies with BS 5062 Part
1”.

Attention was also drawn to Section 6 of the Health and Safety at Work Act (1974), which lays
out the general duties of designers, manufacturers, importers, suppliers and installers, and the
more specific duties concerning research, testing and instructions for use.

4.1.2 Where Choice of Surrogate Affects Arrest Forces

*Human being and rigid test weight*

In a similar prominent series of tests in the USA as reported in Boeing Company (1967), the use
of “anthropometric articulated dummies” in drop testing highlighted the dangerous deficiencies
of using waist belts and chest harnesses as fall-arrest body containment devices. Additionally, a
study of dynamics was made by comparing the maximum arrest forces recorded in the drop tests
mentioned above with similar drop tests but using rigid test weights instead. The conclusions of
Boeing Company (1967) were to the effect that the maximum deceleration force in a drop test
using a rigid test weight was about twice in comparison with an identical drop test with a human
being. Steinberg (1977), comments on the findings and adds a note of caution to the effect that:
“additional verification with a variety of FAS and fall conditions is needed”, and that “the
comparison is empirical and is based on very limited data”. The reasons given for the difference
are that in a real fall situation the human body will dissipate a significant amount of the energy
generated from the fall, due to its complex, articulated viscoelastic structure. Flail, rotational
and jackknifing motions, compression of the body, redistribution of body organs, internal
friction, and abrasion of straps on clothing all contribute to the dissipation of energy.

*Sand bag and rigid test weight*

In Dickie (1975), a Construction Safety Association of Ontario research programme is
documented, which was arranged to test fall arrest belts, lanyards and lifelines. The intent of the
programme included the development of a test procedure that could be used in a Canadian
Standards Association Certification scheme. Over 300 lanyards were tested during the course of
the research. A drop-test weight of 100 kg mass was used in preference to a “semi-rigid” sand
bag which was reported to have been in use in prior testing conducted in Canada. Dickie reports
that the sand bag, being somewhat flexible, “did not give reproducible results because it
responded differently on each instrumented drop”. Also, it was determined that the bag acted as
a shock absorber and reduced arrest loads. There is no description given of the sand bag, and no
reasons are offered for the “different responses”. Nor is there any evidence given in support of
the shock absorbing abilities of the sand bag. It is the Author’s own experience that when drop
testing is conducted with the sand bag as shown in Figure 5, from EN 364 (1992), that
successive drop tests tend to compact the sand grains in the bag.
This leads to a greater grain density in the bottom of the bag than in the top, and therefore affects how the arresting force is transmitted through the bag. However, significant differences only usually occur during the initial drop-tests in the series, mainly due to the fact that the bag is of simple, regular shape, and the sand grains are therefore limited in free movement.

If, however, the cited Canadian sand bag had been more human-like in shape, for example as reported elsewhere in Armstrong and Waters (1969), it can be seen that sand grains in this arrangement are relatively free to move around the enclosed bag, which could lead to test reproducibility difficulties and could explain the bag’s shock absorbing ability.

**Full system testing or testing individual components**

Dickie (1975) then proceeds to consider whether the fall arrest equipment should be tested as individual components or as a complete FAS in the research programme. The drop-testing and certification of both lanyard and waist belt together is cited as the then current practice in Canada, but this is argued against, for a number of reasons.

First, Dickie argues that, in actual usage, the lanyard is replaced far more frequently in use than the waist belt. Therefore it is possible for the owner of the waist belt, in replacing the lanyard, to choose one having a different length or material and, by doing so, creates a completely different FAS for which no certification exists. If, on the other hand, the belt and lanyard are tested and certified independently of each other, then the new lanyard will, regardless of length and material, be a certified product. Steinberg (1977) agrees with this course of argument, and adds that individual components must meet certain criteria independent of one another, and therefore there will be no reliance on other components within a FAS which cannot be guaranteed, especially the anchor. Steinberg also argues that individual component testing makes test procedures simpler, which enables manufacturers to gain individual component certification and therefore facilitates the sale of separate components.

Whilst this argument appears to be sound at the first reading, there is no guarantee when tested together that components will behave in the same manner as when tested separately. This is because individual component based test methods may not reproduce actual FAS applications of use. This approach does make sure that all components are tested and certified, but it may not detect system-based safety issues, as reported graphically in Clark (1985), and as recommended in BS 5062 (1985). In Steinberg (1977), it is conceded that some types of equipment do have to be tested together, for example where shock absorbers are integral to a fall-arrest device or lanyard, or in the case of vertical rail based systems, both trolley and rail must be tested together, because of interaction reasons.

Second, Dickie argues that the lanyard acts as a shock absorber, which substantially affects the load transmitted to the body containment device during an arrest. Variations in lanyard size, length and material produce significant differences in loadings. [Author’s note: whereas modern day obligations require integral energy-absorbing devices in lanyards, which largely control and limit the applied arrest force in a drop-test, this was not necessarily the case in certain countries around the world in the date of the report under discussion, i.e. 1975. Nevertheless the information is discussed, due to its relevancy to this review]. Dickie continues to argue therefore that when full FAS are tested, the load that the containment device experiences is controlled by whatever lanyard the manufacturer wishes to use. This in effect ensures that there is no common standard for a containment device to meet. Therefore, by testing the containment device on its own it ensues that all such devices are subjected to the same test criteria.
Finally, Dickie puts the same argument forward for the lanyard; the loading of the lanyard is affected by the shock absorbing qualities of the containment device. Therefore separate testing for the lanyard removes the variation attributable to different thickness and materials of webbing used in containment devices, as well as configuration, stitching patterns, etc.

Whilst the second and third arguments are very persuasive, what cannot be ignored is that in a FAS the components do interact with each other in a way to dissipate energy, indeed that is one of the main purposes of a FAS. Indeed, testing in such circumstances is realistic as this is the way in which the equipment will be used. However Dickie’s argument is only concerned with arrest force, as the sole criterion in the test.

More modern day thinking, as reported in Occupational Safety and Health Administration [OSHA] (1999), describes the USA’s legal rulemaking approach regarding fall protection in the construction industry. To quote: “OSHA’s approach in the final (State) standard is to address personal fall arrest equipment on a system basis. Therefore, OSHA does not have separate requirements for “fall arrestors”, “energy absorbers” and “self-retracting lifelines/lanyards” because it is the performance of the complete system, as assembled, which is regulated by the OSHA (State) standard. OSHA’s (State) standard does not preclude the voluntary standards writing bodies from developing design standards for all of the various components and is supportive of this undertaking”. In these terms, the performance of the complete system is seen as a legal requirement, whereas the performance of individual components that make up such systems is seen under the remit of voluntary standards.

**Test results**

Other researchers, e.g. Clark (1985) and Reader (1969a) have used other responses of the FAS which can be either measured or discerned in some way. In any event, when considering the preliminary waist belt test results in Dickie (1975), maximum arrest forces are reported to vary from between 16.9 to 21.4 kN. This shows that even when using a rigid test weight, there can still be a wide variation in test results, and therefore the previous argument that test weight is preferred to the sand bag because the sand bag could not give reproducible results, cannot be wholly upheld. The results show that reproducibility of results do not just depend on the choice of test surrogate, but also on how the FAS under test responds to that surrogate, and also depends on other factors such as variations in fall trajectory and in the manufacture of the FAS. It would also seem that the tests specified were too onerous because the arrest load variation is attributed to the amount of tearing of the buckle grommets in the tested waist belts.

The results also show that the argument of testing the waist belt on its own, on the basis that this would produce a standard method so that all belts could be subjected to the same criteria, cannot be upheld. This is because some belts experienced 16.9 kN, whilst others experienced 21.4 kN, in the same test set-up. This is hardly a standard test. The method may have subjected each waist belt to the same amount of drop-energy, i.e using the same test weight, same test lanyard, and same free fall criteria, but the applied loads resulting were 26% more onerous for some test specimens than others.
4.2 FALL ARREST LOAD CONVERSION FACTOR BETWEEN SURROGATE AND HUMAN BEING

In Dickie (1975), it is admitted that the use of a rigid test weight in drop testing would give much harsher results than those experienced by a human being, but no factors are offered. As part of the project, an investigation is conducted to determine what “factor of safety” existed between the developed test methods and what would actually happen to a human being under similar conditions. Since human cadavers were not available for research, and there was too much of a risk of injury involved with the use of volunteers, the determination of the factor became one of estimation supported by some testing.

Six drop tests were carried out to assess the effect on the arrest force concerning the rigidity of the test weight. The comparison is performed, (with no reason given why), with a “semi-rigid” sand bag, (a bag filled with plastic tubes which were packed with sand). This is surprising as the sand bag was previously discredited. No description or specification of the sand bag is made.

For each drop test a 2.44 m long lanyard was used and the test weight / sand bag was elevated as to provide a 2.44 m free fall. Lanyards made from polyamide and polyester were used of 12.7 mm, 14 mm and 16 mm diameters. Arrest force for the rigid test weight was in each case greater than that for the sand bag, the difference varying from between 0.8 to 1.7 kN, the average value being 1.21 kN. This represented a percentage increase of arrest force on the test weight of between 7.09 and 14.76%, the average being 11.7%.

Dickie then claims that the factor of safety is 1.117:1, but more tests should have been conducted, especially given the number of different types of lanyard used. Also, for instance, if the factors of test weight, lanyard length or free fall distance had been varied, a different factor of safety may have emerged, or a specific factor for each set of circumstances. Dickie then goes further and states that the factor of safety can be estimated as 2, ie a test weight produces an arrest force of twice that which would be experienced by a human being. This is based on the premise that:

- the sand bag was semi-rigid unlike a human and that the kinematics of a human being under arrest will assist in arrest force attenuation
- the sand bag does not compress as much as a human body would
- the test method does not allow for falls with an irregular trajectory such as swing falls which will be evident in actual fall situations, and which will assist in arrest force attenuation.

There is no documentary or test evidence in support of these claims and therefore it is difficult to validate the estimate.
In Sulowski (1978a), an evaluation of commercially available vertical lifeline-based FAS was made. Such FAS types are described in EN 353-2 (1992). In this research report, it is stated that the maximum allowable arrest force according to the Canadian Standards Association requirements at that time was 17.8 kN. This was based on two important assumptions:

- the resistance of the human body to a shock loading in the +a_y direction (producing an “eyeballs-out” reaction), being 9.09g (source not cited) – the equivalent of 8.9 kN force on a mass of 100 kg;

- when related to a “method of testing”, that in the case of a human body, the shock load is 50% of that generated when employing a rigid steel test weight. This possibly refers to conclusions of Boeing Company (1967), and/or Dickie (1975).

This is expanded upon by describing a hypothetical Canadian Association drop-test, in which an arrest force of 17.8 kN would pass the test, and would be expected to register only 8.9 kN, (17.8÷2), when arresting the fall of a human body.

Sulowski (1978a) then argues that this standard requirement is unsatisfactory for the following reasons:

- The factor of 2 used for converting the results from a rigid test weight to a human body is not supported by enough evidence and was questioned by some researchers. Also, apparently, other standards had stated that the factor should be 1.5 to 2.

- That newer evidence had shown that 8g was the injury threshold to a shock load in the abdominal area for a jackknife type of reaction, (source not cited), ie 7.85 kN for a 100 kg mass.

Consequently for the purposes of the Sulowski (1978a), the maximum allowable arresting force was lowered to 8 kN, together with a maximum duration of 300 ms and an allowable second arresting peak of 50% of the maximum recorded. The duration was defined as the time during the maximum arrest peak at which the force was larger than 50% of the maximum value.
4.2.1 Force-Time Curve Characteristics

Sulowski (1978a) also makes important observations in regard to the recorded output of the drops tests, the “force-time” curves. These curves are the visual representation of the arrest force sequence, as measured with load-sensing apparatus with respect to time, and allow the verification of the maximum arrest force to be made, and allows other criteria to be assessed. An example of a force-time curve is shown in Figure 10, after Riches (1998a).

![Figure 10: Typical example of force-time curve output of drop-test.](image)

Figure 10 describes the outcome of a drop-test conducted with a vertical rail and trolley-based FAS, using a Hybrid II fully anthropomorphic, articulated test dummy of 75 kg mass in place of a human being. Consequently this is a full FAS test, with the full body harness being worn by the dummy in the same manner as would a human being. The dummy is released at time \( t = 0 \), and free falls for a period of approximately 350 ms before any significant decelerative force is applied by the operation of the FAS.
This allows the calculation of the free fall distance using the constant deceleration formula:

\[ S = ut + \frac{1}{2}gt^2 \]

Where:

- \( S \) is distance of the free fall event in m
- \( u \) is initial velocity in m/s (equal to 0 at the point of release)
- \( g \) is acceleration due to gravity (taken to be constant over the free fall event) = 9.81 m/s\(^2\)
- \( t \) is the time of the free fall event in s.

Therefore \( S = 0 + \frac{1}{2} \times 9.81 \times (0.35)^2 = 0.6 \) m.

At \( t = 375 \), there is a substantial rate of onset of force, indicating that the arresting mechanism of the device is operating, which is near constant until the maximum arrest value of 3.5 kN is reached at \( t = 500 \). The rate of onset is approximately equivalent to \( 3.5 \text{ kN} \div 0.125 \text{ s} = 28 \text{ kN/s} \), which is equivalent to a jolt of 373.33 m/s\(^3\) or 38 g/s for a 75 kg mass. Note that these values can only be valid at the point and direction of measurement, which in this case was at the sternal harness attachment point on the dummy, in head-to-toe vertical alignment.

During time \( t = 500 \) to \( t = 625 \) the arrest force rapidly decays, indicating that the energy-dissipating feature has done its main work, and that the residual energy remaining is insufficient to cause further actuation of the dissipating feature. In effect the whole FAS stretches and then relaxes, rather like a spring vibration, and during \( t = 500 \) to \( t = 625 \) the dummy is rebounding upwards. During time \( t = 625 \) to \( t = 680 \) the dummy falls again causing a smaller arrest peak of nearly 1.5 kN. Subsequent classical damped spring-vibration action of the system ensues with decreasing peaks, as residual momentum is depleted, and at time \( t = 1125 \) the dummy is at rest in suspension. This can be seen as the registered force remains constant at approximately 0.75 kN, which is the approximate weight of the clothed dummy (0.75 kN being roughly equivalent to a 76 kg mass under the Earth’s natural gravitational action of 9.81 m/s\(^2\) or 1g).

In Sulowski (1978a), it is admitted that the use of the rigid test weight in the drop-tests described in the report does not entirely describe the shock to which a falling person is exposed. The force-time vibration-like characteristics of two specific force-time curves are referred to, and comments are made to the effect that such characteristics may not have occurred if a human body had experienced the arrest. In other words the outcome of the arrest force and its characteristic with respect to time is affected by the response of the test surrogate.

### 4.2.2 Force - Falling Weight - Acceleration Relationships

Also in Sulowski (1978a), a mathematical formula is developed to be used to estimate the maximum value of arrest force in a particular FAS. It is in this context that the “conversion factor” becomes important – i.e., the factor between the force imparted to a weight in a drop-test as compared to that of a human body in a similar situation. This factor is taken to be 1.5 to 2, based on “experiments by others”, but whose work is not referred to. The formula to some extent is verified by experimental evidence but, more importantly, describes an important relationship between values of falling weights, arrest force and imparted deceleration, which is often misunderstood in the fall-arrest industry.

The formula shows that the imparted deceleration to a falling weight during arrest, by way of a simple lanyard connected to a structure, will increase as lanyard stiffness increases and as free fall increases. It decreases with the increase in falling weight and increase in lanyard length.
However, a decrease in deceleration with an increase of falling weight should not be misinterpreted as a subsequent decrease in maximum arrest force, as shown from the results of experiments in Sulowski (1978a). Excepting size of falling weight, all other factors remained constant, Table 2 refers.

Table 2
Experimental results of simple lanyard drop tests after Sulowski (1978a)

<table>
<thead>
<tr>
<th>Mass of falling weight (kg)</th>
<th>Maximum arrest force (kN)</th>
<th>Imparted deceleration (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>47.816</td>
<td>48.86</td>
</tr>
<tr>
<td>145</td>
<td>56.045</td>
<td>39.37</td>
</tr>
<tr>
<td>190</td>
<td>65.386</td>
<td>35.00</td>
</tr>
</tbody>
</table>

4.2.3 Conversion Factor Between Rigid Weight and Articulated Manikin/Human

In research reported in Sulowski (1978b), reference is made to the importance of dynamic drop-testing in the evaluation of FAS and how, in the Canadian national standards of the time, a steel, rigid weight of 100 kg mass was employed to simulate the weight of a falling person. This is quite an important statement, since the rigid weight surrogate can only simulate the weight of a human being, and no other attribute.

In the same research, it is asserted that since the energy absorbing properties of the rigid weight are different to those of a human body, the acceleration imparted to the rigid weight during a drop-test arrest sequence will be different than that imparted to a human being in identical circumstances. The basis for the research was to identify how the two accelerations differed, and to express this as a “conversion factor”, i.e., the acceleration imparted to an arrested weight divided by that imparted to a human being in identical circumstances. It was acknowledged that because of the dangers associated with such testing, the use of human volunteers was not an option and, as a result, available literature on the subject was scant. Whilst some previous research, (not directly referred to), proposed a conversion factor of 2, the consensus of research at the time recognised the need for further investigation. This was due in part to the proposal treating the conversion factor as being constant, i.e., not having regard for variables such as free fall or the energy absorbing characteristics of the FAS in question. Consequently, an anthropomorphic, articulated manikin was drop-tested in a series of tests, the results of which were compared with similar tests with a rigid weight.

The manikin was more commonly known as the Sierra “Stan” model, part No. 292-850, of Sierra Engineering Company design. This was a lifelike anthropomorphic, articulated manikin which represented a 50th percentile male according to United States anthropometric data after that contained in Health, Education and Welfare sources, and in Air Force sources after Hertzberg et al (1954). The 50th percentile designation refers to fundamental anthropometry such as weight, stature height and other main body dimensions. A detailed specification of Sierra Stan is found in Sierra (1968). This model was used by other researchers, as in Armstrong and Waters (1969) and in Marsh (1974). [Author’s note: The Sierra Engineering Company, along with other surrogate manufacturers such as Alderson Research Laboratory and Humanetics have subsequently been acquired by First Technology Safety Systems. A detailed history of test surrogates can be found in First Technology Safety Systems (1998)].
This research, and other independent research, was reported in Ulysse and Sulowski (1982), in an attempt to try and define load test conversion factors for various types of test surrogate. It was thought important because standards and regulations in most countries required the use of rigid masses when testing fall arrest equipment and systems. Again, given that testing with volunteers was considered to be too dangerous, it was important to know what factor should be applied to results in order to relate them to the human body.

A ratio of decelerations, “C” or conversion factor between the maximum deceleration of an arrested rigid mass to that of an arrested articulated manikin or human being was defined as:

\[
C = \frac{a_{RM} + 1}{a_M + 1}
\]

where: \(a_{RM}\) is the maximum deceleration registered with the rigid mass;

\(a_M\) is the maximum deceleration registered with an articulated dummy or human being;

the assumption being that all test surrogates have the same weight.

An equivalent formula for the ratio of maximum arrest force is also given.

Two test programmes were arranged, one in Canada and one in France. The Canadian drop-tests were performed with a rigid test mass of 99 kg and with the Sierra Stan full anthropomorphic articulated dummy of 84 kg, as reported above. (The basic mass of Sierra Stan was 73.5 kg, which was increased to 84 kg as a result of putting overalls, waist belt, and load cell on dummy).

Conventional waist-belts were used as the body containment device, and a mandrel in the rigid test weight allowed the fitting of the belt in a similar fashion to around the waist. Drop tests were conducted with lanyards of 12 mm and 16 mm diameter 3-strand nylon, and of 6 mm and 8 mm wire rope. Free falls were between 0.6 and 1.95 m. A second series of tests was performed on three commercially available vertical lifeline based FAS in accordance with the Canadian standard of the time, CSA Z259.2 (1979), which was in the course of drafting. Such systems are described in EN 353-2 (1992).

Two types of vertical lifeline based FAS were tested in France with human volunteers of mass between 77 and 87 kg, as well as with a limbless manikin with an attached cube form to represent the neck and head. This manikin is reported to have an approximate mass of 80 kg. It was considered to be rigid or elastic depending on whether it was attached through its lifting eyebolt or through a full body harness.

The degree of difficulty in interpretation of results associated with the two approaches, arises from:

- The use of full body harnesses in the French tests and waist-belts in the Canadian tests. The values of “C” would be influenced by the body containment device.
- The Canadian comparison was between full dummy and rigid test weight, whereas the French tests were between human volunteers and a limbless manikin.
- The difference of masses of the test devices. In the Canadian tests there was a difference of 15 kg between the heavier rigid test weight and full dummy. In the French tests there was a maximum difference of 7 kg between human volunteer and limbless manikin.
Mention is made in Ulysse and Sulowski (1982) of the differences in mass between test subjects, and that the results were adjusted to take them into account. There is no explanation as to the method of adjustment, which raises some degree of doubt in regard to the conclusions. However in Sulowski (1978b), the research preceding Ulysse and Sulowski (1982), a formula is proposed to introduce a correction for the difference in the mass of the Sierra Stan manikin and the rigid weight. This formula is neither justified nor discussed.

**Canadian research results**

In the case of the Canadian tests, the results were plotted on graphs of “C” verses free fall distance as per Figure 11, and some results for “C” are shown in Table 3 below.

<table>
<thead>
<tr>
<th>Lanyard type</th>
<th>Free fall (m)</th>
<th>“C”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ø 6 mm wire (7 x 19 SS)</td>
<td>0.25</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>2.00</td>
<td>1.4</td>
</tr>
<tr>
<td>Ø 8 mm wire (fibre core)</td>
<td>0.25</td>
<td>2.85</td>
</tr>
<tr>
<td></td>
<td>2.00</td>
<td>1.6</td>
</tr>
<tr>
<td>Ø 12 mm rope (3 strand nylon)</td>
<td>0.25</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>2.00</td>
<td>1.0</td>
</tr>
<tr>
<td>Ø 16 mm rope (3 strand nylon)</td>
<td>0.25</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>2.00</td>
<td>1.4</td>
</tr>
</tbody>
</table>

As can be seen from the results, “C” was not constant and decreased with increased free fall, irrespective of lanyard type, and was generally larger for the stiffer wire ropes.

![Figure 11: Graph of “C” verses free fall distance for different types of lanyard](after Ulysse and Sulowski (1982))
The results of the second series of Canadian tests with the three commercially available vertical lifeline based FAS are shown in Table 4.

### Table 4
Canadian research results for “C” with vertical lifeline based FAS

<table>
<thead>
<tr>
<th>Arrester device</th>
<th>Lifeline</th>
<th>“C”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sala Everest 1011</td>
<td>Ø 8 mm 6 x 37 wire rope with fibre core</td>
<td>1.14</td>
</tr>
<tr>
<td>Komet Kibloc with Souplex Shock absorber</td>
<td>Ø 16 mm 3 strand nylon rope</td>
<td>1.15</td>
</tr>
<tr>
<td>Sala Everest 6006</td>
<td>Ø 12 mm 3 strand nylon rope</td>
<td>1.22</td>
</tr>
</tbody>
</table>

The second series of results do not report the actual free fall figure, so it is difficult to comment on the results. (Different arrester devices may have different lengths of connecting lanyard). What can be said is that the “C” value varies with the type of FAS in question.

It was claimed that in the tests there was a visible difference in the final speed between the rigid test weight and full dummy at low free fall distances. How this was verified is not explained. The difference is rationalised by referring to the aerofoil drag of the full dummy, (having a prone pre-release position), but this is unlikely to have made a great difference. However it is acknowledged in the prior research, Sulowski (1978b), that in the testing, speed nor any other aerodynamic parameter was measured, and hence the aerodynamic rationale is hypothetical and would need further investigation.

If aerodynamics was a significant influence, then one would expect a greater difference at larger free falls, (given that the most influencing factor in the equation for aerofoil drag is the square of velocity), which was not evident.

However this idea of different final velocities is pursued to the point of claiming that because the final velocity of the full dummy was lower, the final fall energy of the dummy would be lower, explaining why the maximum arresting force on the dummy was lower. However, other factors have to be considered. The final fall energy has to be evaluated not just with respect to kinetic energy, (velocity related), but also with respect to potential energy, (height related) and strain energy, (stiffness related). In actual fact the centre of gravity of the full dummy travelled further than the centre of gravity of the rigid test weight in the tests, (due to the jackknifing nature of the dummy in the waist-belt, the centre of gravity position moves outside of the dummy’s body), so that the dummy continued to contribute energy to the system even during deceleration, due to its position, which can be seen in Figure 12. Also, the compressibility of the dummy’s body must have been a factor. This could be observed by the fact that the rate of onset of arrest force on the full dummy was always smaller than that on the rigid test weight.
Finally it is claimed that the value of “C” becomes lower at greater free fall heights because the energy dissipating nature of the dummy reaches a limit, whereby the lanyard assumes a greater energy dissipating function by elongating to a greater extent. It is hypothesised that “C” may tend to a value of 1 as free falls increase to infinity.

Figure 12: Displacement comparison between test weight and full dummy [after Ulysse and Sulowski (1982)]

French research results

In the case of the French tests in Ulysse and Sulowski (1982), a value of “C” is given for the limbless manikin of 3.5, and 4.5 for the human volunteers. Although not clear, it is assumed that these values have been obtained by comparing the limbless manikin and human volunteers with similar tests utilising a rigid test weight. The value of 4.5 is shown as an average value, with no statement of calculation and, for both values, no free fall or arrest force measurements are given. It is stated that the values of “C” are greater than those of the Canadian tests due to the use of full body harnesses in the French tests. However, due to the number of different factors involved and the lack of documentation, it is difficult to substantiate that conclusion.

The two results that are presented show testing on a vertical wire cable lifeline based FAS, with free fall heights of “less than 1 cm”. This could be referring to the amount of slip of the arresting device on the lifeline, but is not made clear. The rigid test mass, limbless manikin and two human volunteers of 81 kg and 88 kg mass were drop-tested and registered arrest forces of 7 kN, 2.45 kN, 1.91 kN and 2.45 kN respectively.
One further result is presented which tests an 11 mm diameter single mountaineering rope-based lanyard with shock absorber of 2 m overall length. This is tested in conjunction with a full body harness at the dorsal attachment point, using a human volunteer of 88 kg mass and the limbless manikin of 80 kg mass. The free fall height was 2 m and the direction of fall was feet-first. The reporting of the results is incomplete, but the human test has maximum arrest force and system elongation figures of 3.8 kN and 1.5 m respectively.

Despite the lack of documented results, it is claimed that in the case of the shock absorbing lanyard tests, there was no significant difference between the maximum arrest force registered on the limbless manikin and the human volunteer. Hence “C” is close to 1. The explanation for this is that the shock absorber dominates the arresting response irrespective of test subject.

**Conclusions**

The conclusions in Ulysse and Sulowski (1982), are difficult to follow given the different types of test, eg: different body containment devices, the lack of documentation, and the uncertainty in regard to the number of tests actually carried out. There is also the uncertainty in regard to how adjustments were made for the differences in masses between test subjects and surrogates.

It is claimed that the value of “C” is not likely to be known with great accuracy due to the dangers of tests with volunteers, and that the substitution of the human body with a full dummy may only give approximate results. Another claim is that because “the value of “C” from the tests is always equal to or greater than 1”, standards and regulations that call for drop tests employing a rigid test weight will produce higher results than those produced on a human body in similar circumstances. This is an unknown safety factor, which depends on FAS type and free fall. However this can only be asserted for arrest force, which is not the only criterion in deciding whether a FAS is safe or not. In any event, the limited results that were presented show that, in full FAS testing with a full body harness, the value of “C” is nearly 1, ie a negligible safety factor. Also the conclusions can only be asserted for the size of masses, free fall distances, and FAS types that were under test.

The main conclusion from the earlier research paper, Sulowski (1978b), which formed a basis for the Canadian work reported on in Ulysse and Sulowski (1982), was that the conversion factor of 1.14 to 1.22 found for vertical lifeline based FAS challenged previous understanding. The draft of the standard CSA Z259.2 (1979) had previously allowed a maximum arrest force of 17.8 kN on vertical lifeline based FAS, based on a falling 100 kg mass, at a conversion factor of 2. This meant that there was an expectation that if 17.8 kN was registered in a drop-test with the 100 kg mass, then a human being would experience an actual maximum arrest force of 8.9 kN, (17.8 ÷ 2). However, Sulowski (1978b), had shown, to some extent, that the conversion factor could be lower, at around 1.2. Using this factor, a human being would experience an actual maximum arrest force of 14.8 kN, (17.8 ÷ 1.2). This was unacceptable, as vehicle crash research had indicated at the time that 8g, (producing an equivalent of approximately 8 kN force on a 100 mass), was the injury threshold for the abdominal area, as reported in Sulowski (1978a).

[Authors note: vehicle passenger restraints under research and test were predominantly waist belts, so information from such research was of interest to the fall-arrest industry, which at the time utilised waist belts as the body containment device].

Consequently, a recommendation was put forward for the lowering of the maximum arrest force value in CSA Z259.2 (1979). This was adopted and the 17.8 kN value was lowered to 12 kN. Therefore at the factor of 1.2, the 12 kN level would be expected to produce 10 kN on a human being (12 ÷ 1.2), but this was still higher than the 8 kN abdominal injury threshold.
Other research

In other work, Sulowski (1982), which focuses on the requirement for a mathematical formula to predict maximum arrest force in a given FAS, further analysis and discussion is given to the value of “C”, since this value is a factor in the formula.

It is stated that the conversion factor “C” should be defined as the ratio of acceleration imparted to a rigid test weight to that of the acceleration imparted to a full articulated dummy during an arrest of a fall under similar test conditions. The argument for this centres on the dangers of drop-testing with human volunteers, and cites the common practice in the automotive and other industries to use full articulated dummies to represent the human being in dangerous situations.

A research project is cited in Sulowski (1982) which deals with this matter, Sulowski (1978b) as mentioned above, in which it was established that the value of “C” varies with respect to free fall distance and the type of lanyard connection employed. The argument is put from these results that where falls include an element of free fall greater than 2 m, then it safe to assume that C = 1, ie there is no difference in arrest decelerations between a full articulated dummy and a rigid test weight. It is also stated that the value of C = 1 should be used when a full body harnesses is employed as the body containment device in a FAS.

This proposal comes from drop-test results comparing the elastic properties of both waist-belt and full body harness based FAS, and consequently their respective capabilities to reduce arrest force. However a confusing factor appears in that the waist-belt drop tests were conducted using a rigid test weight, whereas the full body harness drop tests were conducted using a full anthropomorphic, articulated dummy. Perhaps it would have been more appropriate to have tested like with like, eg: drop testing both the waist-belt and full body harness based FAS with the full dummy.

In ANSI A10.14 (1991), a standard for fall arrest equipment, reference is made to the “force factor”. This is defined as the ratio of arresting force on a rigid metal test weight to that of a human body having the same weight with both falling under identical conditions, and is given a value of 1.4:1. As with most standards, no justification or information is given, but the implication is that the test weight will apply 1.4 times more maximum arrest force than that experienced by a human being. This has often been interpreted to mean that if a FAS is drop-tested using a 100 kg rigid test mass for certification reasons, a person of up to 140 kg may be able to use the equipment safely, (140 ÷ 100 = 1.4). However, this is a very dangerous assumption, because other researchers above have shown, even if to a limited extent, that any “factor”, if present, depends on type of FAS, design, and free fall, i.e the factor is not constant. The other important point is of course whether such a FAS could cope in terms of strength and energy dissipating capacity with the effect of increasing the free fall energy imposed on it by 40% (40% more mass being equivalent to 40% more energy being developed during the period of free fall).

Other researchers have commented on differences in fall arrest forces between different test surrogates, for instance in Drabble (1995). Drop-tests were conducted on a horizontal lifeline-based FAS, with a full anthropomorphic, articulated dummy, and a test weight, for comparative purposes. Each surrogate was of 100 kg mass and was attached in turn via a webbing lanyard of 2 m length to the horizontal lifeline. No energy absorbing devices were utilised and drop-test configuration was identical in each circumstance, with a free fall of 2 m. Arrest tensions in both the webbing attachment lanyard and in the horizontal lifeline itself were approximately 15% more severe with the test weight than with the dummy. This was explained by referring to the compliant nature of the full body harness worn by the dummy, and the compliancy of the dummy itself, which are factors that were not present when testing with the weight.
Also, in Fairbairn (1980), reference is made to previous test experience. It was purported that tests in which a test weight connected to a test structure by a lanyard of 2 m length, and allowed to free fall over a distance of 2 m, caused arrest forces that were approximately 25% greater than with similar tests conducted with a full articulated dummy. It is worth noting that in Fairbairn (1980), the test programme was commissioned by the British Standards Institution as a means of checking the feasibility of the then chosen deceleration criteria for the arrest of persons wearing industrial safety belts or harnesses fitted with lanyards both with and without energy absorbers. This had stemmed from recommendations made by the Royal air Force Institute of Aviation Medicine, Farnborough, that personnel wearing abdominal belts should be subject to no more than 5g deceleration in an arrested fall, whilst 10g was a safe upper limit when wearing a full harness. [Author’s note: In this respect, it is worth drawing attention to Reader (1979), a Royal Air Force Institute of Aviation Medicine report. In this, a safety harness development was reported on. The purpose of the harness was to arrest the inadvertent fall of crewmembers from aircraft whilst in-flight, eg: helicopter winch-men performing search and rescue work. For the drop-testing, “a 95th percentile male dummy weighing 107 kg dressed in a lightweight coverall and modified lifepreserver” (inflatable lifejacket) was used to simulate the fall from an in-flight aircraft. It is mentioned in this report that “safety harnesses are usually tested to 10g for strength”, but there is no reference to support this assertion.]

Fairbairn (1980), utilised a 95th percentile anthropometric dummy, (based on its weight of 97.5 kg), and also measured localised acceleration in the head of the dummy for research purposes in the az and ax planes. It is also worth examining the 186 or so drop tests reported in Fairbairn (1980) from the repeatability viewpoint. Except a small number of tests which were conducted using a rigid test weight, the use of the anthropometric dummy, combined with frequent calibration of the measuring equipment throughout the test programme, resulted in results with a great degree of repeatability. For instance, in a series of 28 consecutive drop-tests of 2 m free fall, conducted with lanyards of 2 m length, with slightly different rope constructions, arrest forces of $7.16 \pm 0.63$ kN were produced. Also in Fairbairn (1993), in five consecutive drop-tests of 1.08 m free fall, arrest forces of $10.36 \pm 0.95$ kN were produced. This shows that drop-testing with more complex test surrogates such as full dummies need not necessarily lead to test results with poor repeatability, as when compared to results with more simplified test surrogates such as rigid steel weights. Well thought out and reproducible test methods, coupled with sensible calibration frequencies can have a significant affect on the ideal to eliminate measurement error.

**4.3 COMPARING RESTRAINT LOADS FROM DIFFERENT TEST SURROGATES IN VEHICLE CRASH PROTECTION RESEARCH**

In Armstrong and Waters (1969), a substantial test programme was undertaken to establish a technical basis for a dynamic test specification for compliance of vehicle seat belts. Hitherto all testing was static only, but it was agreed that since the seat belt performed its function under dynamic conditions, it should be tested under such conditions.

It was also recognised that the development of a dynamic test for vehicle restraints would have to be directed towards a relatively simple, inexpensive, reliable and reproducible test. The use of an elaborate and expensive dynamic test would make it impossible to sample a statistically significant portion of the annual production of seat belts, which at that point in time numbered some 50 million.
One area of investigation centred on the choice of test surrogate. Because of cost and test reproducibility reasons, a test dummy with minimum articulation was preferred. It was therefore necessary to determine to what degree articulation could be eliminated while still reproducing human behaviour in the seat belt. Dynamic compliance testing had to be realistic as possible within the limits of economic capability.

At the time, there were a number of very sophisticated anthropomorphic dummies used for research purposes. They were designed to perform in a manner which approaches human behaviour under impact deceleration. The initial cost of such devices and their upkeep was such that it was thought to be economically infeasible to use such devices for compliance testing.

To develop data for a less costly, more rugged device, a series of tests of five surrogates with varying degrees of articulation were made, and were compared to human kinematics under crash conditions.

These test surrogates were:

- A wooden torso block of 73.5 kg mass, distributed as per the Alderson Research Laboratory (ARL) F-50 dummy, and without any form of articulation. This had a neck stump, and arm and leg stumps, and appears identical to that shown in Figure 5, except that the leg stumps were horizontally disposed, to facilitate the seated position.

- The ARL Military F-50 dummy of 79.4 kg mass, which was a wooden, full dummy with basic articulation.

- An American National Bureau Standards (NBS) sandbag of approximate human form and of 73.5 kg mass. The contents of the bag was a mixture of sand and sawdust so arranged that the mass distribution of head, torso, arms and legs was the same as the F-50 dummy.

- The ARL VI-50 experimental dummy of 73.5 kg mass. This had a high degree of articulation, with cervical and lumbar spine sections, a pliable thorax and a realistic pelvic structure.

- The Sierra Engineering Model 292-850 of 73.5 kg mass. This also had a high degree of articulation, with cervical and lumbar spine sections, a pliable thorax and a realistic pelvic structure, but also had some internal structures simulating human anatomy.

The resistance to movement of each dummy’s joints could be set by way of frictional adjustment. Each had their joints set at 1g. This meant, for example with the arms, that the friction setting would be increased until the joint was locked, and then would be slowly decreased until the arm just fell under the influence of gravity.
Each of the surrogates were strapped in turn into a vehicle seat with a lap-and-shoulder strap type seat belt. Each seat and occupant were accelerated in the fore and aft plane until a velocity of 12.2 m/s was reached, and then were decelerated at 30g over a stopping distance of 0.48 m. Loads in the straps were measured. Simple proportional adjustments were made for the differences in surrogate mass. Simple extrapolations were also made of data from tests conducted on human volunteers in similar test circumstances, but from velocities of 6.1 m/s at a deceleration of 16g over a stopping distance of 0.23 m. The maximum loads (total of load in lap strap plus load in shoulder strap) are shown in Table 5.

<table>
<thead>
<tr>
<th>Test Surrogate</th>
<th>Total of loads in lap and shoulder straps (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torso body block</td>
<td>43.43</td>
</tr>
<tr>
<td>ARL F-50</td>
<td>37.24</td>
</tr>
<tr>
<td>NBS sandbag</td>
<td>33.51</td>
</tr>
<tr>
<td>ARL VI-50</td>
<td>29.24</td>
</tr>
<tr>
<td>Sierra 292-850</td>
<td>25.05</td>
</tr>
<tr>
<td>Human (simple extrapolation)</td>
<td>18.90</td>
</tr>
</tbody>
</table>

Undoubtedly it would have made more sense to run extra tests to compare the surrogate behaviour with that of humans, by subjecting all tests to the 16g criteria, and not having to rely on simple extrapolations. As with all predictions, they are fraught with uncertainties, especially where the extrapolation exceeds the last data point by more than 15% of the known data range. In this case the extrapolation was nearly 50% past the last data point. Project budgets prevented further testing.

What could be concluded, however, from this data in Armstrong and Waters (1969) is that as articulation of body parts and pliability of the torso part of the test surrogate decreases, the loads in the body restraint increase, in the case of vehicle crash simulations. The load factor comparing the wooden torso to human was 2.3, and in the case of most sophisticated dummy to human, 1.3.

More detailed tests were conducted using the more lifelike dummies, the Sierra 292-850 and Alderson VI-50, but it was concluded that it was not practical to construct a full anthropomorphic dummy which produced seat belt loads that were equivalent to those produced with human beings. Also, those which approached the required performance were not durable enough to withstand the repeated tests which would be required in a dynamic compliance test programme. Further, the initial cost and upkeep of the dummies which approached human likeness dictated that special low cost, simplified dummies designed especially to produce the required seat belt loads should be developed.
It would transpire however, after reviewing later papers, that the rationale of producing low cost simplified dummies was not pursued, as reported in King (1993) in which the Hybrid III and EUROSID full anthropomorphic dummies are reviewed. In Foster et al (1977), the Hybrid series of dummies is reviewed, each progressing with higher degrees of sophistication. Hybrid I was developed in 1971, as a development of the Sierra 292-1050 design, which took account of interchangeability of parts and hence ease of repair. Hybrid II was developed in 1972 and was the first dummy to have acceptable repeatability combined with good durability and serviceability. Hybrid III was developed in 1975.

Yet higher degrees of sophistication are reported in Pearlman and Viano (1996), where the pregnant female version of the Hybrid III is reviewed, complete with an internal 28 week old representation of a foetus. In National Highway Traffic Safety Administration (1997), an advanced frontal crash test dummy is described, named THOR, (test device for human occupant restraint).

4.4 USE OF FULL BODY ANTHROPOMORPHIC ARTICULATED DUMMIES IN FALL-ARREST TESTING

4.4.1 Use of Vehicle Crash Test Dummies in Fall-Arrest Testing

It is interesting to note that the fall-arrest industry has adopted the use of vehicle crash test dummies at certain points in time, probably because of expediency, and that no substantial research has been conducted in regard to the development of a full anthropomorphic dummy specifically for fall-arrest testing purposes. Not all researchers mention the name, trademark or specification of the dummy utilised in their programme of testing, but where this has been done so, it would appear that a significant number come from the field of vehicle safety research. For instance, the use of the Hybrid II dummy has previously been reported in Mattern and Reibold (1994), and in Riches (1998a). In Kloss (1998), a Hybrid III model was utilised.

The whole concept of relating data from tests with anthropomorphic-articulated test dummies to actual situations with human beings was reported to be “very difficult” in Amphoux (1982). In this research, testing was conducted by using an “anthropometric manikin”, as specified in NF R 10-101 (1971), which is the French standard for anthropomorphic dummies used the dynamic testing of motor vehicles. This particular model of dummy was also specified in NF S 71-020 (1978), which was the French standard for fall arrest equipment up to 1992. Amphoux comments that: “extrapolation from a mannikin, whose biomechanics can only be an imperfect model of the human body, is always tricky”.

In Arteau and Giguére (1988), a Humanoid Ltd 95th percentile articulated manikin was utilised, (with hip joints fixed in a seated position). No mention is made to what body dimensions the 95th percentile measurement refers.

The Sierra model 292-850 anthropomorphic articulated dummy as previously reported in Armstrong and Waters (1969), was also utilised for the fall-arrest testing described in Marsh (1974). Measurements of acceleration of the head, tension in the harness webbing, and the recording of dummy kinematics by using high speed photography, are all documented. The dummy is recorded as having a mass of 74.4 kg with a stature height of 1.73 m. An additional test surrogate was also utilised in the form of a 136 kg rigid torso shape. In the recommendations of Marsh (1974), it is suggested that the Sierra dummy is utilised to assess the performance of harnesses, whilst the rigid torso shape could be utilised in a dynamic strength test, ie to establish the upper limit for the harness’s restraint capability.
4.4.2 Assessing Safety Harnesses for Human Factors Criteria

The arrest of a fall and the prevention of any injury presents a challenging problem to engineers and designers of FAS. The system must be robust enough to withstand normal use, commensurate with ergonomic requirements, Riches (1997), whilst at the same time have energy dissipating characteristics that minimise injury in the case of an arrested fall. In Arteau and Giguère (1988), a number of available test methods are discussed in regarding to determining a method to assess full body harnesses for strength and human factors criteria. Mention is made of the dynamic behaviour of harness straps, and the corresponding need to take into account the elasticity of human tissues. This elasticity could cause slipping or translational movements of straps over the body, which could induce instability and hence affect the properties or behaviour of the harness. In consequence, “soft body behaviour” was an important factor to take into account.

Arteau and Giguère (1988), discusses drop-testing using full anthropomorphic articulating dummies by referring to test methods in standards at the time that utilised these surrogates, eg: the French standard NF S 71-020 (1978), and the British standard BS 1397 (1979). A number of parameters relating exclusively to the dummy are cited, each of which offer a number of options, which in turn could affect the outcome of the test.

These are:

Specification of Dummy:
- different models from manufacturers
- basic dimensions and masses, (5th, 50th and 95th percentile)
- morphology ~ mesomorph, ectomorph or endomorph¹
- number of joints

Joint Adjustment:
- completely loose
- with some degree of friction

Pre-Drop Attitude:
- feet-first, head-first, prone or supine
- erect or folded over

Comparison is made with rigid torso shaped masses, examples being quoted from the Australian standard AS 1891 (1983), and the German standard DIN 7478 (1980). Since this type of surrogate does not have a head, limbs or joints, the main parameters mentioned for the full anthropomorphic dummy are the same, except for joint availability, adjustment and relative position of limbs to body. Whilst the torso’s surface is generally hard, being made from a hard wood, it can be covered by a softer but resilient polymer-based material. Again, shape is stated as being important, with several manufacturer’s types in existence.

¹ Form and structure of body — a mesomorph describes a person with a muscular body build; an ectomorph describes one of thin body build; an endomorph one of fat and heavy body build.
After discussing drop-testing concepts, Arteau and Giguère (1988) proceed to apply those concepts in a series of tests on a new type of “vest-harness”. This harness was designed to automatically pull the legs upwards in a fall-arrest situation, and hence allow the harness occupant a more seated position. Initially, slow lifting and static suspension tests were performed with human volunteers, as reported in other research literature. Each test was commenced with the subject being raised from one of five starting positions, in an attempt to simulate the lack of control of the body when stumbling over an edge in a fall situation. These positions were:

- A - standing, with 45º backward hyperextension of legs (legs at 45º to the head-to-toe axis)
- B – standing, erect
- C – sitting, with legs straight, together and at 90º to torso
- D – sitting, with legs together and folded into body, with upper part of leg at 45º to torso
- E – prone, with 45º backward hyperextension of legs (legs at 45º to the head-to-toe axis)

It was discovered that when staring from positions C and D, that the suspended subject could virtually slip out of the vest-harness, buttocks first, if they were of the endomorph shape, (waist circumference larger than thoracic circumference).

As a result, a full series of drop-tests, which were going to be conducted using a Humanoid Ltd 95th percentile articulated manikin, were curtailed. Instead, a limited series of tests were conducted. No mention is made to what body dimensions the 95th percentile measurement refers.

Drop-tests were conducted over a free fall of 1 m via a lanyard connected to the dorsal harness attachment point. The lanyard was 1.52 m long of 16 mm diameter 3-strand nylon rope. The articulated manikin had an anatomy such that the hip joints were fixed in a seated position. This is typical of test surrogates used in vehicle crash protection testing, where part of the restraining system is the seat itself. Arteau and Giguère (1988) claim that the fixed seated position of the manikin was not a limitation to the drop-testing on the basis that, because the buttock fall-out problem was known beforehand, the test objective was to know if, with the thigh straps disconnected, the fall-out could still occur. During testing, fall-out did not occur; the manikin was arrested by the belt and vest part of the harness bearing on the lower rib cage.

Subsequent discussion in Arteau and Giguère (1988) leads one to realise that other drop-testing was conducted with the full articulating manikin but with the thigh straps of the vest harness in place. In this circumstance the buttock fall-out problem was not reproduced. The reason given for this is that the waist circumference of the manikin was smaller than the chest circumference, which presumably allows the waist belt element of the harness to gain some purchase on the manikin’s form.
This is cited as a limitation in the use of anthropomorphic manikins, because their fixed dimensions do not reproduce the wide variety of human morphology. However, the fixed-hip nature of the manikin could not have assisted in the nature of the tests and the particular operation of the harness in question. Also, since the fall-out problem had been discovered during slow lifting of human volunteers from the starting positions “C” and “D”, see above, (both seated positions), then the pre-release positions of the drop tests should also have been in similar configuration. In this way, the anthropomorphic manikin may have shown the fall-out fault, if not completely, at least partially. However, since the manikin was of the fixed hip type, articulation of the legs about the hip may have been limited, and the range of movement is not referred to in the tests, but it would be a main factor to consider concerning the onset to fall-out. Probably the manikin would not have been able to be released from position “D” because of the fixed-hip nature.

Identical tests for comparison purposes were made with a rigid torso-shaped mass, similar to that shown in Figure 6, but based on the Canadian standards specification, CSA-Z259.10 (1990). This is reported to be made from several slices of hardwood held together by steel rods and is an “approximate reproduction” of the 97.5th percentile American male as compiled by Diffrient et al (1974). The mass is nominally 100 kg. No mention is made in regard to which dimensions are representative of the 97.5th percentile. The results of the tests were that fall-out did not occur; the torso-shaped mass was arrested by the belt part of the harness bearing on the armpit representation. An additional test was conducted with the thigh straps correctly in place; again no fall-out was reproduced. Arteau and Giguère (1988) simply comments to the effect that the limitations of the torso-shaped mass are more important than with the articulated manikin, since there are no arms, no legs, and no articulation. In fact all the torso is, is a mass with a shape suitable to fit into a harness.

The main conclusion from Arteau and Giguère (1988), is that each of the tests is limited in its discriminating power, and a pass in one type of test need not mean that all other tests will be passed. None of the tests on their own give a complete answer to the problem of body-containment in FAS. Consequently, a number of complementary approaches are needed to measure it and to understand it fully, which may involve suspension testing with humans and drop-testing with more than one type of surrogate. This was the approach taken in ISO 10333-1 (2000) and in the draft of ISO/CD 10333-6 (2000), wherein tests with human beings, rigid torso masses and anthropomorphic dummies were advised.

Arteau and Giguère (1988) proceed to discuss the limitations with this approach in that the capital cost of acquiring and operating equipment for testing are an important influence. Test weights and sand bags may cost between £500 to £2000; rigid torso-shaped masses, such as utilised in EN 364 (1992), may cost in the region of £5000 to £7000; and full anthropomorphic dummies may cost in the region of £2000 to £20000, depending on the degree of bio-fidelity and on-body measurement needed. Human suspension testing has a less tangible cost, but is typically made up of “volunteer pay”, medical supervision and insurance. The need for calibration and expert support is also a cost factor, especially with the full anthropomorphic surrogates, as is durability, ie repair and replacement frequency, due to damage occurring in tests.
This point is taken up in Sulowski and Brinkley (1988), where it is suggested that test weights and rigid torso-shaped masses would prevail in use because of their lower cost and the relative independence of the test results from a full dummy’s initial position and adjustment of friction joints. However, fully articulated dummies, with vehicle crash-protection type neck and lumbar joints, and bio-fidelity suitable for drop-testing, are available at costs of £6000 to £7000, as in First Technology Safety Systems (1998), which compares with current torso-shaped mass costs. Also as mentioned elsewhere in this review, as in Fairbairn (1980), repeatability of test results is not just a function of the surrogate being used, but with all sources of error in the test set-up.

However if test cost and simplicity are the only concerns, as they may well be where routine testing is necessary, eg: for quality control reasons, then simple forms of surrogate will suffice. However, as reported in Arteau and Giguére (1988), and in Clark (1985), this approach may not detect critical design errors when assessing designs for the first time, for legal or certification reasons, or where a certain feature requires particular scrutiny. In Noel (1982), 67 drop-tests were performed with a full anthropomorphic manikin of 77 kg mass, (type not specified), to investigate the effects of pendulum falls. Accelerometers were mounted on the chest to allow measurements in the $a_x$ and $a_z$ axes, (the latter being the axis of pendulum swing). The manikin was released in various attitudes to simulate the variety of pre-fall positions of the body; these included head-first, feet-first and horizontal trajectories at various lanyard angles, typically at 30-50° to the vertical. In some cases the manikin was wrapped in the test lanyard in order to simulate lanyard entanglement in a fall. The investigators were looking to see if the lanyard would get round the manikin’s neck in such an entanglement situation. In these drop-tests the manikin would spin about the $a_z$ axis as the lanyard unwrapped, whilst simultaneously undergoing a pendulum motion with respect to the test anchor point. The strangulation of the manikin was not observed during these tests. An interesting point to note is that the $+a_x$ acceleration was always higher than that recorded in the $-a_z$ axis. For instance with a taut 2m long lanyard with integral energy absorber, with a pendulum pre-release angle of 50°, $-a_z$ accelerations of 4.9g and 5.4g are recorded with corresponding $+a_x$ accelerations of 10.6g and 10.3g respectively. Energy absorber elongation was very low.

4.4.3 Characteristics and Limitations

It is of importance to note some of the discoveries and assertions made in other research, especially in regard to kinematics and the containment of the harness on the body. In substantive research as reported in Crawford et al (1990), part of the testing involved the simulation of arrested falls in various attitudes, by using an articulated, anthropometric dummy of 100 kg mass, wearing various forms of tree-climbing harnesses. In one particular test, concern was expressed in how there was a tendency for the sit-belt element of the harness to slide over the buttocks of the dummy, and but for the lodging of straps in the mechanical hip or ankle joints of the dummy, the dummy would have dropped to the test house floor. This test was repeated a number of times to establish the tendency.

Comment was made to the effect that although the moulded exterior of the dummy was of necessity much stiffer that of human flesh, (for test durability reasons), the harness in question nevertheless demonstrated a tendency to slip and cause fall-out of the body. This, and the lodging of the straps in the dummy’s joints, raises important questions in regard to the use of such surrogates.
Results could be adversely affected or beneficially improved by the use of dummies. To facilitate the articulation of joints in some dummies, particularly the hip-upper leg joint, there is a gap between the lower part of the torso and the leg. This gap can entrap the leg strap of a harness, which may affect the outcome and geometry of the drop-test, either adversely or beneficially. Dummy manufacturers have responded to this problem by narrowing the gap between body and limb, by using different hip bearings or gaiters or shrouds which do not have a drastic effect on articulation, as in Platten (1989). This has been supplemented in some cases by fitting the dummy with stiff canvas shorts, or other attire, as in Ogle (1989).

In other research as in Crawford (1996), a series of drop-tests was conducted to simulate falls in sit and full body harnesses used by tree surgeons, by using an Ogle anthropometric dummy, (a full anthropomorphic, articulated dummy). [Author’s note: Ogle Design Ltd have subsequently been acquired by First Technology Safety Systems. A detailed history of test surrogates can be found in First Technology Safety Systems (1998)].

It is stated in this research that all drop-tests were conducted with the dummy in the head-up position, i.e. with a feet-first trajectory. The reason for this approach was based on the claim that this trajectory was known to lead to the highest arrest forces for any given drop height and rope type, because the kinetic energy of all the major body parts, (torso, limbs and head), acts in the same line of force. Further justification and explanation is given, in the claim that whilst falls from the supine position might appear to be worst case physiologically, during arrest the bending of the dummy leads to energy dissipation with a consequent reduction in arrest force. Furthermore, such a trajectory had caused structural damage to dummies in previous test series with the consequent loss in consistency of results.

This raises the question of durability again, because limitations should not have to be placed on tests because of known deficiencies of test equipment. Part of the problem arises from the fact that, generally, these types of surrogate have been designed for other forms of impact testing, e.g. occupant containment in vehicle crash protection, or in aircraft ejection, where the dummy is extensively supported by a seat, through which the vast majority of the impact energy is transmitted. Consequently the same dummies may not have the necessary strength or durability for arrested falls in free space, where there is no support, and all energy transmission is via the containment straps.

Utilising full anthropomorphic, articulated dummies in applications for which they were not designed does create limitations in their use. For instance in Edwards and Neale (2000), test surrogates were chosen to take the place of a human driver in order to assess lap strap restraints in the event of the overturning of a tractor. Two types were utilised; the EuroSID, which was designed for side impact testing of vehicles, and the Hybrid III, which was correspondingly designed for frontal impact. The problem with both dummies is that neither were designed to represent behaviour in the omni-directional impact situation seen in a tractor overturn.

In Hulme and Mills (1996), investigations are made into the traditional test methods for industrial safety helmets, because of the perceived deficiency of those methods. It is asserted that manufacturers were designing helmets to pass the tests in standards. Therefore the standards needed to be improved with more realistic tests, for the helmets to improve in design and protection. Traditionally, helmets for test were secured to a rigid head form, and impacts were applied vertically downwards to the crown of the head, where the force is transmitted directly through the neck. It is asserted in Hulme and Mills (1996) that, in a real accident, it is more likely that an impact will be off centre rather than directly onto the crown, and that a lateral or oblique impact on the head will result in rotation of the head and neck.
To assess the more realistic response of the head in such a situation, taking into account injury thresholds, it was decided to investigate the response of heads and necks of anthropomorphic, articulated dummies such as the Ogle OPAT dummy and the Hybrid III. After careful analysis, however, it soon became apparent that various physical qualities of the neck forms could not reproduce the actual human behaviour when struck on the head. After reviewing the Swedish RID neck (rear end dummy – used in vehicle impacts applied to the rear of the vehicle), it was decided to construct a new neck design for the OPAT dummy, to give a more realistic stiffness and to be omni-directional in response.

4.4.4 Detecting FAS Design Deficiencies by Observing Kinematics

As mentioned extensively elsewhere in this review, several researchers studied kinematic behaviour, eg: in Rushworth et al (1986), Rushworth and Mason (1987), Amphoux (1982), Mattern and Reibold (1994), Clark (1985), and Reader (1969a) and discovered two general design deficiencies with FAS. The reason they were able to observe these deficiencies is because, where they were not able to use human volunteers, they used full anthropomorphic articulated dummies, as being the next best substitute.

The first deficiency concerns the straps of the safety harness. They change position in response to fall arrest forces and, as demonstrated in the research mentioned in the paragraph above, are able to put pressure on vulnerable parts of the body, such as head and neck or armpits. The second deficiency concerns the operation of the FAS as a whole. Historical and modern certification systems around the world often require the testing of individual pieces of equipment, with relatively simple test methods. There are good reasons why this is done, and these have been discussed in clause 4.1.2. However, when certain combinations of equipment are connected together to form a FAS, they may not behave in the same way as when they were tested separately. They may also need to be tested in a more complex fashion as a FAS, than when tested as individual pieces of equipment.

A classic example of this is the use of retractable arrestingers, ISO 10333-3 (2000), and tripod anchor devices, ISO 14567 (1999). The tests which these pieces of equipment must pass to meet the above standards are different compared to the test they must pass when combined, ISO 14567 (1999). This raises issues of compatibility between the pieces of equipment, and issues of performance. The differences in outcomes of tests performed on individual pieces of equipment and when assembled together in a FAS may be insignificant in some cases, or may be catastrophic or fatal in others, as reported with the ladder based FAS in Clark (1985), or in Kloss (1995). Clark (1985) has already been discussed elsewhere. In Kloss (1995), the testing of retractable arrestingers in combination with roof mounted anchors is reported, both pieces of equipment having met their respective individual test requirements. But when they were assembled and brought together in such a way as to allow the lifeline of the arrester to be extracted and retracted horizontally, and to be subsequently dragged over the edge of the roof in a simulated “over-the-edge” fall-arrest, catastrophic failure of the lifeline ensued.

The evidence is clear that there is a need at some point in the design and assessment of the FAS, to ensure that the kinematics of the FAS are such as to not endanger the life of a safety harness occupant. Some dangerous situations are not necessarily easy to foresee, as demonstrated in Riches and Feathers (1998), and as shown in Figure 13. As part of this research, two full anthropomorphic, articulated dummies were simultaneously released (SIMREL) whilst attached to a horizontal lifeline via energy absorbing lanyards. This was to simulate two workers falling together at the same time, as had been reported in a number of case studies of accidents, Health and Safety Executive (1985).
The pre-release point was such that the dorsal harness attachment point, to which the lanyard was attached, was approximately 1.5 m above the level of the horizontal lifeline. This simulated the lifeline being installed at walkway level, i.e. with the worker working above this level. During the drop-test, the review of the high-speed photography revealed that one dummy caught the horizontal lifeline under its armpit during the fall, which caused the arm to be pushed upwards, as Figure 13 shows. In a real-life incident this could have severely injured the worker, and so the test showed up a hazard in allowing a worker to work with a horizontal lifeline installed at the level of the feet. Of course this incident would not have showed up if simple test weights had been used in lieu of the dummy, which is the normal surrogate in use presently to certify horizontal lifeline products, EN 795 (1996).

![Figure 13: A simultaneous release of two dummies being arrested by way of a horizontal lifeline with attached energy absorbing lifelines; dummy “George” (right hand side) catches his arm during the fall. After Riches and Feathers, (1998).](image)

This highlights the deficiencies of using other types of surrogate to the full dummy. One of the main drawbacks of the rigid torso-shaped test mass for instance, especially in the type used for European standard testing at present, EN364 (1992), is that its design has very little regard for anthropometrics, and it has only a partial neck, and no head. The argument for anthropometrics is made, for example, by considering the waist circumference and chest depth measurements of the subject torso test mass, and comparing them with typical anthropometric data tables. The torso waist circumference is approximately 1015 mm, which is greater than the UK adult male 95th percentile waist measurement of 960 mm according to Pheasant (1990), and the UK adult male military aircrew 99th percentile waist measurement of 1010 mm according to Bolton et al (1971). In particular, the latter measurement suggests that less than 1% of UK adult male population have a waist measurement larger than this. The torso waist circumference is also constant from the pelvic area to the chest area, such that there is no waist.
The chest depth – the straight line horizontal measurement from the sternum to the back is 223 mm on the torso test mass, which is very near to the UK adult male 5th percentile chest measurement of 215 mm according to Bolton et al (1971). Virtually all of the UK adult male population are larger than this.

What this means in practice is that manufacturers, when testing on this surrogate, tend to have to produce harnesses with waist straps that are oversize to fit the waist measurement. Also, due to the fact there is no waist, the effect of the waist strap of the harness under test cannot be taken into account since it does not purchase on any part of the torso. This becomes particularly relevant where other types of containment device are tested – particularly simple waist belts which are used for non-fall arrest applications. These items tend to slide up the torso test mass and are lodged under the armpits.

The EN 364 torso test mass was adopted from the mountaineering industry, where its form appears to have been conceived of as a mandrel for static testing, Ginzel (1979). However the mountaineering industry have taken into account the deficiencies caused by the lack of a waist, and have a waist form and dimension specified on their static test torso, EN 12277 (1998), which corresponds to an approximate 50th percentile UK adult male measurement.

The absence of head and neck forms on the torso test masses are perhaps much more serious. In Riches (1998a), and as shown in Figure 14, part of the research and test schedule included some routine tests to be performed on a “trouser harness” – a full body harness sewn into a set of overalls. Drop-tests were conducted in accordance with EN 361 (1992), the European standard for full body harnesses, which requires the use of the torso test mass.

![Figure 14: Post-drop suspension of EN 361 test-torso suspended by trouser harness – failure of a primary joint has caused harness attachment point to pass across the neck stump](image)

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![Figure 14: Post-drop suspension of EN 361 test-torso suspended by trouser harness – failure of a primary joint has caused harness attachment point to pass across the neck stump](image)
In one case, as shown in Figure 14, there was a failure of one of the primary sewn joints on the harness. The test-torso finally came to rest in a tilted post-drop suspension attitude. In fact, the failure had allowed the shoulder straps from the right hand side of the torso to pass over to the left hand side, so that the final resting point of the dorsal harness attachment point was on the left hand side of the torso. For this to happen, the strap system had to pass over the neck stump of the torso. In a real situation this could have broken the occupant’s neck or partially severed the head. If a head form had been present on this surrogate, then the problem would have been quite noticeable – in the event this test result, incredibly as it may seem, is a “pass” under EN 361 (1992).

This is because the dummy “was not released by the harness” and was “arrested in a head up position with an inclined angle of less than 50°”. There is no mention in EN 361 (1992) about fractured components or torn webbing making the test a failure.

In Riches (1998a) another part of the research and test schedule included the testing of a FAS which consisted of an energy absorbing lanyard and a full body harness, both items having previously passed tests on their own merit. Both items were tested together by conducting head-first trajectory drop-tests, using the Hybrid II full anthropomorphic, articulated dummy. The majority of the Hybrid II’s major dimensions are 50th percentile representations, as is the mass, which is 75 kg. The harness in question had been tested with the EN 364 (1992) test torso. Two views of the post-drop suspension attitudes are shown in Figures 15 and 16.

As revealed by other researchers’ discoveries in this review, the shoulder straps of the harness and the collector plate, which gathers the straps at the back of the harness in most conventional designs, were forced against the neck and back of head. Rushworth et al (1986), describes this sort of design deficiency in terms of how a harness occupant could be loose consciousness quickly because of direct pressure on the carotid artery. This was observed during a static suspension trial using human volunteers in Rushworth et al (1986).

This particular test was reproducible and the results could be repeatedly demonstrated. Before testing the harness was fitted correctly and snugly to the dummy’s body, and the design of the Hybrid II hip joint is such that strap ingress into the gap between torso and leg is not a concern.

The main point to make is that the previous testing conducted with the test-torso had not revealed this shortcoming, and since this surrogate has the head and most of the neck missing, one cannot discern the problem.

Other types of problem associated with this kind of strap migration can be seen in Figures 17 and 18. This shows that the chest strap, which in some designs keeps the main body straps in place, can ride up and garrotte the neck. This could be fatal for the occupant. Again, tests with headless test torsos cannot detect this problem, because the offending strap cannot be seen in relation to the neck and head. Sometimes, even by using human volunteers in static suspension tests, these kind of migrating strap problems cannot be detected. This is because in static suspension tests, only the weight of the body is bearing on the straps, so little stretching of the straps takes place. Only if the problem is really exacerbated will it be detected in this type of test. However, the dynamic nature of the drop-test tends to show up these problems because a greater force over a short period of time is induced in the harness, causing quite discernable strap stretch and corresponding geometry changes.
Figures 15 and 16: Views of post-drop suspension attitudes showing shoulder straps forced against neck and strap collector plate forced against back of head.
Figures 17 and 18: Views of post-drop suspension attitudes showing chest strap garrotting the neck
4.4.5 Calculating the Free Space Requirement

Arguably the most important aspect of any FAS is that it must stop the fall of a worker quickly enough before such a fall allows the worker to collide with the ground or other substantial structure, Riches (1997). As can be seen from Section 2, FAS stop the downward motion of a free fall by applying an arresting force over a set distance (the arrest distance), until the worker is brought to a complete halt. Consequently there has to be enough free space beneath the worker to ensure that, if a fall occurs, it will be arrested safely before a collision can occur, i.e. the free space must be greater to some degree than the arrest distance.

This creates the requirement to know how much free space is needed beneath a worker in case of a fall, and is a legal requirement according to Statutory Instrument No. 3139 (1992).

The free space can be calculated by considering such factors such as: worker’s mass, free fall, arrest performance characteristic of the equipment being used, harness stretch, height of worker and safety clearance. An example is shown in Figure 19 after Riches (1999) which considers a retractable lifeline based FAS. Such devices are described in ISO 10333-3 (2000).

The free space is much easier to determine when the FAS in question is tested as a full FAS, with a full representation of a human being, i.e. a full anthropomorphic, articulated dummy. This can be seen from Figure 19, wherein the free space is simply the arrest distance AD (using the dummy’s foot as the datum) plus a safety clearance SC. The safety clearance is similar to the philosophy of a safety factor and is set to take into account such factors as variations in stature height and mass of people, in arrest performance of equipment, in harness stretch, in environment and to allow for dynamic rebound, which cannot be assessed unless viewed by high speed photography methods.

If, for whatever reason full FAS testing is not carried out, a calculation based on the arrest distance contribution of each of the components in the FAS has to be performed. Some of these contributions may have to be estimates, based on individual component performance tests which may not represent how the component may actually be used and may not be the same value as when tested together with other components. Such a calculation is difficult and is prone to error. For example in the above case of a retractable lifeline the following will have to be considered:

- A retractable lifeline is tested under EN 360 (1992) which drop-tests with a 100 kg solid mass over a free fall of 0.6 m with the lifeline of the equipment “clipped off” to prevent retraction. This produces a significantly greater arrest distance than that produced when the equipment arrests in normal use, i.e. the lifeline remains taut due to its retractable nature and there is virtually no free fall, Figure 19 refers. A “factor” has to be estimated for this or else the greater arrest distance has to be used in the calculation.

- The datum for the calculation will have to be set where the test mass connects to the lifeline end termination, since the test mass does not have legs and feet. This datum must be referenced to the walkway properly, by ensuring that it is set a height above the walkway equal to the height of where the harness attachment point would be.

- In performing the free space calculation, an allowance needs to be added to the arrest distance for harness stretch and the height of the worker. In addition, a safety clearance needs to be added, which needs to consider the same factors for the safety clearance as described in the full system test above, but perhaps needs to have greater allowances to cover unknowns that could only be ascertained by a full system test.
ONSET TO FALL

AFTER FALL, IN POST-FALL
ARREST SUSPENSION

RLL

W

G

A

AD

SC

RFS

Key:
A: anchoring point position
RLL: retractable lifeline
W: walk way
G: ground level
AD: arrest distance
SC: safety clearance
RFS: recommended free space

Figure 19  Example of recommended free space for a retractable lifeline
(full system test with anthropomorphic, articulated dummy)
In the revised version, BS 1397 (1956), this dummy was retained, as mentioned in Shand (1960), but at the later revision, BS 1397 (1967), this dummy had been replaced by a torso type of 136 kg to give “a greater safety factor in performance requirements”. At the final revision, BS 1397 (1979), a full anthropometric, articulated dummy was reintroduced, of 100 kg, coincidental with the introduction of deceleration limits for the drop-test. Harnesses, lanyards and shock absorbers were tested together as a full FAS, which if passed successfully, was awarded a British Standards Institution “Kitemark” certificate. This was quite a realistic test, since the equipment would be tested as it would be used, and each part of the FAS would be able to contribute to the energy dissipating process as designed. Correspondingly, levels of arrest force could be kept at a minimum.

BS 5062 (1973) was introduced to cover the rail and cable/rope based vertical systems appearing in the market place, and the dynamic strength test was quite severe, utilising a 136 kg test mass with a free fall of what appears to be 2 m. This was superseded as in BS 5062 (1985), which introduced deceleration limits and the same full dummy as used in BS 1397 (1979). This was partly as a result of work done as already reported in Clark (1985). The arresting devices, their matching lifelines or rails, connecting lanyards and matching harnesses were all tested as a full FAS, and, if passed successfully, were again, as above, awarded a British Standards Institution “Kitemark” certificate. Again, this was quite a realistic test, since the equipment would be tested as it would be used, and each part of the FAS would be able to contribute to the energy dissipating process as designed. Moreover a “system operational test” was introduced to simulate the falling back of a human from the ladder. Correspondingly, levels of arrest force could be kept at a minimum.

In France, the use of a vehicle crash test dummy to NF R 10-101 (1971) was the harness test surrogate for the national standard, NF S 71-020 (1978), although a 100 kg test mass was used for other equipment testing. Interestingly, the harness test was conducted with a test lanyard of 2m length, made from mountaineering rope. The dummy was released so as to fall freely over a distance of 4 m. Four successive drop-tests were conducted in this fashion, two with a feet-first trajectory, and two with a head-first trajectory. The test was passed if the dummy was not released from the harness.

With the advent of the drafting of European standards in the late 1980’s, as the freedom of trade legislation required the harmonisation of national standards, a number of technical and safety merits were lost from national standards throughout Europe. The European standards became the “lowest common denominator” as certain countries could not accept the high performance standards that had been in place in other countries for a considerable period of time. When these standards were published in 1992, after a period of transition, they became a support to the new “CE” legislative personal protective equipment certification scheme, controlled by Statutory Instrument No. 3139 (1992) in the UK. All conflicting national standards had to be withdrawn, and the existing BSI “Kitemark” scheme became obsolete for FAS.

Amongst the negotiations, the UK lost the system test approach, the use of the full dummy, and the 8 kN maximum fall arrest force had to be lowered to 6 kN. One of the significant changes brought about by this compromise affected the vertical rail based FAS, as covered by EN 353-1 (1992). In fact the changes brought about a backward step in terms of safety and technology, and stifled future innovation.
Virtually all of the EN 353-1 systems in Europe were fitted on ladders and were generally designed for a quick and abrupt arrest. So the arrest forces were generally high so that the arrest distance was as short as possible. It goes against the purposes of the system to have a climber falling an excessive distance down a ladder. In the UK, before EN 353-1, these FAS were tested as systems under BS 5062 (1985) as previously stated, - with anchorage line, arrester, lanyard, connectors, harness and an anthropometric dummy. The dummy mass was 100 kg and a maximum of 8 kN arrest force and 1.5 m arrest distance was permitted. Because of the realistic nature of this drop-test, with energy dissipation contribution from the harness and dummy, connecting lanyards could be relatively short and without the need for integral energy absorbers. Arrest forces could be kept as low as 5 to 5.5 kN with arrest distances of around 0.5 m. Referring back to Figure 10, this shows a force-time curve for a drop-test of an EN 353-1 system, but tested using the BS 5062 (1985) method, with the exception that the anthropomorphic, articulated dummy was of 75 kg mass instead of 100 kg. No integral energy absorber was utilised, as can be seen from the characteristic of the trace, and only 3.5 kN was registered, (at the chest harness attachment point). Naturally, this figure would be slightly higher if a dummy of 100 kg had been utilised, but the level would not be expected to rise above 6 kN.

It is worth noting that, in Germany, the corresponding DIN standard did not have a requirement to measure arrest force - so it could have been anything.

Unfortunately, with the adoption of the 100 kg test mass and 6 kN arrest requirement, just about every manufacturer was forced to redesign and equip their sliding arresters with energy absorbers or dissipating elements in order to get under this 6 kN threshold. This was partly because the British Standard relied on energy dissipation from the matching harness and, to a lesser extent, on the compliance of the dummy. The test mass provided neither. The other factor involved was that the manufacturers who relied on the DIN standard had to go from no arrest force requirement, (in actual fact around 7.5 to 10 kN when measured) to 6kN. The disadvantage with adding energy absorbers was that arrest distances had to increase and, given that the undeployed length of a conventional tear-ply energy absorber doubly contributes to the free fall distance, the arrest distance of most arresters got very near the maximum allowed of 1.0 m. In fact, with tolerances required in production it is easy to go above this 1.0 m requirement today. Also, the fitting of energy absorbers to arresters generally makes them much less ergonomic and more expensive - not good news for operating organisations. If the previous regime of testing was adopted, the need for energy absorbers on the sliding arrester devices could be deleted, with no compromise on safety – in fact the FAS would be safer and more consistent in arrest performance. However, many manufacturers today still have problems in consistently getting under the 6 kN requirement, even with energy absorbers included – because of the need for an abrupt arrest on ladders. This was in evidence recently when the German delegation to the CEN/TC 160 WG2 standards committee asked for the deletion of the arrest force requirement in EN 353-1 (1992).

The perceived need for the use of a full, anthropomorphic, articulated dummy for fall-arrest testing has been confirmed in other quarters, as in Korhonen (2000). In this communication it was confirmed that in the Finnish Test Institute, drop-testing of harnesses had been conducted with a full dummy, and that a great number of design defects had been observed which could not be detected by using the test-torso without neck and head in identical tests. This included harness straps being held against the neck and head, causing potential compressive injuries as a result of dynamic tension in the straps, and garrotting of the neck by poorly designed chest straps. In Korhonen (2000) it was discussed why the Europeans had not adopted the use of such important test apparatus, given that so many prominent researchers had used full dummies extensively, and given the importance of detecting life-threatening defects during testing. The suggested conclusion was the fear of the unknown – i.e. proposers of the use of full dummies in drop-testing all tended to have test experience, whereas people against their use generally tended to not.
However, the European Standards are not mandatory requirements, they are merely one route to satisfy the “basic health and safety requirements” as laid down in Statutory Instrument No. 3139 (1992). In fact, according to Statutory Instrument No. 3139 (1992), they “must retain the status of non-mandatory texts”. This allows the certification of safety products via other routes, especially where the current suite of European standards do not contain adequate requirements and test methods to assess a safety product’s features against the basic health and safety requirements. An example of this is found in BH Sala (1995), a promotional video film. In this, a new design of variable geometry harness is described. Conventionally, a worker may be connected to a structure via a pole belt at the waist attachment points on a harness in work positioning mode. Should the worker fall, the harness alters its geometry whilst simultaneously absorbing energy, such that the means of attachment is transferred away from the physiologically vulnerable waist attachment points to a safer sternal attachment point. In order to test such an innovation, EN 361 (1992) and the use of the test-torso was inadequate, so a new test procedure which included a full anthropomorphic, articulated dummy was devised. Joint articulation, with the more accurate anthropomorphic characteristics and anthropometry of the dummy was essential in testing such a variable geometry device.

Nevertheless there are difficulties in specifying the attributes of an anthropomorphic, articulated full dummy for fall arrest purposes, especially in a voluntary technical standard, as has been apparent from the discussion over ISO/CD 10333-6 (2000), and as mentioned elsewhere in this review. It has been a topical problem, as mentioned in Clark (1985), whose work was instrumental in the introduction of such a surrogate into BS 5062 (1985), and creating a resolution within the ISO fall-arrest standards committee in 1985 for a similar approach. After a considerable deferred period of ISO standards work due to the work needed to introduce the present European standards, the full dummy approach was re-initiated in ISO/CD 10333-6 (2000), which included a detailed dummy specification, but this was subsequently not adopted. This specification anticipated the reported problems in Platten (1989), which had identified the issues of harness strap entanglement in joints, locking/friction settings of joints, anthropometry, morphology and cost. A detailed specification was essential, because even though previous British Standards utilised full dummies for testing over a considerable time span, specification was either basic or very limited, according to the information contained within BS 1397 (1947, 1956 and 1979) and BS 5062 (1985). In practice, the dummy used was a high specification model, Marsh (1974). The French standard NF S 71-020 (1978) also utilised a high specification vehicle crash test model, as specified in NF R 10-101 (1971).

**Anthropometrics**

The specification of anthropometrics will also continue to remain a problem, however, unless the fall protection industry recognises the stances that have been taken in other impact biomechanics industries such as the aircraft ejection seat, parachute and vehicle crash protection disciplines. One of these stances has been to adopt 50th percentile data throughout the body, after the “Humanscale” data from Dreyfuss in Diffrient et al (1983), and in other data, which represents people with average proportions for their respective height. This data is representative of the “average” person, and the frequency of 50th percentile measurements appearing in the human race is very high as when compared to the other extremes, eg 5th and 95th percentile values.
The Humanscale data recognised that the basic criterion for accommodating designs to people of different sizes is knowledge of their body measurements. Unfortunately, comprehensive anthropometric surveys are difficult and expensive to conduct. Large samplings are taken by the armed forces to make the man-machine relationship successful in a fighting environment, but although these measurements are accurate and comprehensive they are limited to select groups. Civilian surveys have not been extensive in terms of samples and measurements, and a number of them are out of date and need to be corrected for the rate of growth of people’s height which is about 0.8 cm per decade, Diffrient et al (1983).

A comprehensive anthropometric survey includes male and female adults and children. It has to be large enough to represent the total population, including people of different localities, ages, races and socio-economic levels. Measurements are taken by highly trained technicians using standardised methods. The body is measured in various postures and, for accuracy and consistency, without shoes and clothing. The Humanscale method was established by considering data from over 130 military and civilian sources, with special emphasis being placed on the more important surveys in terms of accuracy, sampling and recency.

The Humanscale data represented people with average proportions for their respective heights. A person of any percentile in stature height was given average measurements for that height, because it was recognised that if all the largest percentile measurements were assigned to the large percentile person and the smallest percentile measurements were assigned to the small percentile person the results would be unrealistic and unworkable. A full dummy was built using all the 95th percentile measurements throughout, and the overall result was grossly disproportionate, as reported in Platten (1989). The point being that no-one has all their body measurements based solely on 95th percentile values. Some body measurements may be 95th percentile, but others may be 30th, 45th, 71st, and so on.

The Humanscale data therefore set critical body dimensions which were not statistically treated or averaged out. These were:

- Stature height
- Eye height
- Sitting height
- Eye to seat height
- Buttock to knee height
- Knee height
- Shoulder width
- Hip width (sitting).

Other proportions were statistically approximated, Diffrient et al (1983). Allowances were made for the three body types of endomorph, mesomorph and ectomorph as defined on page 47, and for various world regions, e.g:

- Japanese and other Orientals were found to have about the same sitting height as whites, but their legs tended to be shorter
- Blacks were found to have longer legs in proportion to their trunks than whites.

By adopting the Humanscale data a representative dummy can be designed. This does not preclude the fact, however, that other impact biomechanics industries have recognised the need for other sizes and sexes of dummies, where such differences have a critical effect on testing. This can be seen from promotional brochures as in First Technology Safety Systems (1999), which offers 5th, 50th and 95th percentile male dummies and 5th percentile female dummies for the aerospace industry. There are also 98th and 3rd percentile males for the US Navy.
Whereas the adoption within Europe of various standards has substituted the full dummy with a torso mass, this has not of course meant that the full dummy can no longer used. The use has already been mentioned in BH Sala (1995), and with other organisations who are considering the merits, as in Sanko (2001), and in research and development programmes for the establishment of a full dummy for fall-arrest purposes, Feldstein (1999).
5. CONCLUSIONS

The conclusions are derived from the findings of this review, as based on the scrutiny of over 120 references as detailed in Section 7. A number of references searched for were not obtainable or were not received at the time of writing. These are: Air Standard 61/1 (1975), Dahnke et al (1976), Wexler (1950), Mackersay (1958), and Heisner (1965).

It is accepted that there may be other literature or information which the Author is presently unaware of, the contents of which could affect this review.

A number of different drop-test methods have evolved over time which use one or a number of the following test surrogates:

- Solid, rigid weight of regular shape
- Sand bag of regular shape
- Rigid quasi-human torso shape, without head and limbs
- Full body anthropomorphic, articulated dummy, approximating to a human being

Test surrogates are used in place of human beings for test purposes because of the risk of injury and for ethical reasons. This raises the question of how representative tests with surrogates are as when compared to identical tests in which a human being is used. Selection of test surrogate is often based on the type of test being performed at the time, the influence of testing performed in allied impact biomechanics industries, the reasons behind the testing, testing philosophy, availability of facilities, expediency and cost.

- Some degree of experimental testing has been conducted with human volunteers for the purposes of collecting human impact tolerance data. This has been done at relatively low levels of impact acceleration. Most of the data is for young adult males from the military aerospace field, which arguably represents a small section of the working population [pp 13-14].

- Drop-tests conducted with human volunteers in parachute harnesses for the purposes of realistic parachute opening simulations have produced tolerable decelerations of 5 - 12g according to subject mass (98.4 – 112 kg) at a force equivalent of 4.9 - 13.2 kN. Such decelerations were applied in the a_z axis via parachute shoulder riser straps. With the body restrained in a harness and in a seat, with the back and head fully supported, swing-tests in the a_x plane have produced tolerable decelerations of 3.5 – 16g [pp 14-15].

- Other parachute tests conducted with human volunteers in free fall descents from aircraft, have recorded tolerable opening forces of between 7.3 – 10.6 kN [p 20].

- Human beings have different proportions and comparative dimensions and, therefore, have a mixture of percentile values. A person having a 75th percentile weight may not necessarily have a 75th percentile stature height and waist circumference. Consequently, possible inadvertent disengagement from the containment system can only be detected with human beings with a large enough permutation of dimensions critical to the test in question. This is one difficulty which arises in the use of human volunteers [p 15].
• The use of human beings can be a useful tool especially in the slow lifting and suspending of the subject in a safety harness, which in effect simulates the slow-motion application of fall-arrest force, albeit in a static application, and at a level much lower than that of the actual dynamic level of arrest force. Such a test has been introduced for the first time into a FAS standard, ISO 10333-1 (2000), to check for dangerous interference of the safety harness components on the body [pp 15-17 and 48-49].

• Drop-tests conducted with human volunteers in industrial fall-arrest harnesses for the purposes of feet-first trajectory fall simulations have produced tolerable decelerations of 4.8g over a free fall of 0.6 m, with a force equivalent of 4.27 kN. Such decelerations were applied in the –a direction via a steel cable attached to either the dorsal or sternal harness attachment point [pp 15-16].

• Several researchers have demonstrated that impact testing should not just assess dynamics, ie measurement of accelerations and forces, but that it should also assess kinematics – how the body and containment means reacts and moves in response to arrest. Strap kinematics must never threaten any organ in a fall-arrest situation and the corresponding change in harness shape as a result of dynamic forces being applied must not strangle the worker. However, harness straps have been demonstrated to rise up on the body and to cause injury. Chest straps have become very tight and have lifted to garrotte the neck or strike the face, and shoulder straps have struck the back of the head. Serious head and neck injuries are demonstrated. Inner edges of harness straps have been shown to apply pressure to the carotid artery, which in one case caused the subject to almost lose consciousness except for the rapid intervention of the testing staff. Strap induced injuries were found to be exacerbated for subjects with larger neck circumferences. These design deficiencies had not been revealed by other methods of test [pp 14-17, 19-20, 52-57].

• Feet-first drop-test trajectories whilst useful, are of limited value, since in a fall, body orientation is highly variable. It is apparent that little evidence is available concerning arrest force tolerance in such realistic situations; researchers therefore use “realistic” anthropomorphic, articulated test dummies instead, to avoid the risk of injury to a human volunteer [p 17].

• Feet-first trajectory drop-testing has been conducted with human volunteers to assess the bio-fidelity characteristics of a Hybrid II anthropomorphic, articulated dummy. Deceleration data was compared with deceleration tolerance data from vehicle crash test protection sources. Adapting deceleration tolerance criteria from other impact biomechanics fields has to be done with extreme caution. Impact exposure limit criteria are not determined solely by human biology alone, but are also dependent on body-support and restraining system used to transmit the restraining force to the subject. Tolerances are also dependent on what direction deceleration is applied, and how the body is restrained. For instance aircraft ejection criteria only apply with the spinal column being kept erect [pp 17-19].

• It is apparent that most of the established fall-arrest knowledge is based on previous aerospace research and not vehicle crash protection research [pp 13-14, 18-20].
Different parts of the body may experience higher or lower levels of deceleration than that measured at a single suspension point, due to the body’s structure and the resulting means of transmitting impact impulses. Other impact biomechanics fields tend to limit their impact criteria based on one specific area of the body. They also tend to use acceleration as a criteria, and not “force”, as is done in the fall-arrest industry. Also the duration of acceleration and jolt have limits too. Exposure limits are also set in terms of probability of injury and fatality instead of oversimplified concepts of a single tolerance limit [pp 13-21].

Head-first, prone and supine fall trajectory drop-testing has been conducted using a Hybrid III anthropomorphic, articulated dummy. Deceleration data was compared with deceleration tolerance data from vehicle crash test protection sources. It is arguable that car crash deceleration criteria are not applicable to fall-arrest circumstances [p 19].

Drop-testing research has been conducted which compared results with parachute opening criteria which proposed a limit of 12 kN. This limit was arbitrarily halved to 6 kN to give the generally accepted fall arrest force limit of today’s standards. This level might be limited to a feet-first trajectory only, based on shoulder structure strength which is more vulnerable in a head-first trajectory fall [p 20].

Other criteria are cited as being equally important, namely acceleration duration, levels of jolt and jolt duration – which have limits in other impact biomechanics industries, but not in the fall-arrest field, probably due to the complexity of measurement. There have been some force-duration limits laid down in some standards, one of 100 ms and one of 300 ms [pp 20, 33].

Head jolts have been recorded in head-first fall trajectories using anthropomorphic, articulated dummies, but accuracy is debatable because of the way that the dummy’s neck structure responded in comparison with that of a human being [p 20].

Some drop-testing has been conducted on animals in an attempt to extrapolate findings to human beings, but this has been a matter of controversy. A tolerance level of 8.9 kN was established as a human arrest force using this approach [pp 13, 21].

Human cadavers have been utilised mainly in other impact biomechanics research, but because of limitations in using these surrogates, have been confined to the development of highly realistic anthropomorphic, articulated test dummies [pp 13, 20-21].

There appears to be a distinct lack of information concerning female impact tolerances, and information concerning FAS issues as they affect female workers. Apart from the development of female anthropomorphic articulated dummies as reported in for example, Pearlman and Viano (1996), and in First Technology Safety Systems (1999), the only other source that was found to be of interest was that of Gryfe (1991). This particular work referred to over 200 other papers [p 46, 63].
There is a choice of test surrogates available in all impact biomechanics fields, because some tests are simple and therefore require a basic type of surrogate, such as a test weight. Some tests are regulatory, however, and the selection of surrogate is predetermined. What has to be recognised is that each type of surrogate attempts to be a substitute for a human being in various degrees of sophistication, and therefore the person who analyses the test results must be aware of the limitations imposed by the degree of sophistication. A rigid test weight for example, can only represent the total weight of a worker; it cannot represent any other human attribute [p 23].

Tests have been shown to demonstrate that although a particular type of FAS could meet the drop-test criteria of standards at the time, which used a test weight, when tested in actual conditions of use, under “man-fall” conditions, by using a full dummy as a test surrogate, the same FAS could not arrest the fall. The same tests showed that when potentially incompatible FAS components were mixed together and tested under man-fall conditions, critical deficiencies could be exposed which could not be detected by testing the same components separately, with a test weight or any other surrogate. A similar approach highlighted the fatal deficiencies of using waist-belts as body-containment devices for fall-arrest protection [pp 24-29].

Standards in the past have included test methods to reflect fall trajectories which are realistically likely to happen in use [pp 28, 60-62].

Standards in the past have tested under man-fall conditions to the extent that workplace geometry and the full FAS are included in the test process. Anchor line, matching connectors and matching safety harness were then certified together under an industry recognised and regulated approach. Where alterations, modifications or substitutions of components to the matched FAS were required, it was an encumbrance on the purchaser to re-test to ensure that the new combination would work [pp 28-29, 60-62].

Arguments are also put for individual component testing and certification. Testing and certification is simpler, ensuring that components meet certain criteria independent of one another, and therefore not relying on other components within a FAS that could not be guaranteed. It also facilitates sales. The problem with this is that individual component testing may not reflect how the components are used and, therefore, may have to be very onerous to cover a range of circumstances. Certainly, testing the component responsible for the energy-absorbing function on its own with a test weight will be more onerous than when tested with a matching safety harness [pp 30-31, 42, 61].

It would appear from proposed American legislation that both individual component testing and full system testing will be adopted [p 31].

Even when successive fall-arrest components are tested on their own there can still be a wide variation in arrest force test results, which cannot be used as a criterion for a “standard test”. The repeatability of test results is not solely dependent on choice of test surrogate, but also on FAS response to the surrogate, measuring equipment error, variations in drop-test trajectory, and variations in the manufacture of the equipment [pp 29-31, 35, 43].
• Sand-bag test surrogates allow drop-testing to be conducted with the advantage over rigid weights in that damage to test specimens is less likely, and consequent interference with electronic measurement. However, sand-bags may respond differently during drop-testing due to grain distribution altering during successive tests. This can affect reproducibility of the test and repeatability of results [pp 29-31].

• Substantial research appears to have been concentrated on the apparent differences in arrest force levels in identical drop-test circumstances, as a result of using different types of test surrogate. This has been in an attempt to determine what levels of arrest force would be experienced by a human being under similar circumstances. Some have purported that this factor, termed “the conversion factor – C”, has a value of 2 for rigid test weights, that is the arrest force measured when using a rigid test weight is twice that which would be measured if using a human being in identical drop test circumstances. This is due to the energy dissipating qualities of the harness containment system and the human body itself. Such information was utilised in a standard which allowed a maximum 17.8 kN arrest force in drop-testing conducted using a test weight, on the basis that this would register 8.9 kN on a human being under identical test circumstances. However there is insufficient evidence for this approach [pp 29-33].

• More realistic values of C were researched, because many of the world’s standards were conducting drop-testing with rigid test weights and it was thought important to know what factor was really being applied to results compared to that which would be experienced by a human being in an arrested fall. A great deal of this research is difficult to interpret, due to the way comparisons are drawn between different types of surrogate, and the documentation is unclear at certain points. What is clear, however, is that C is not a constant and, in simple lanyard based drop-tests, decreases with respect to increased free fall, irrespective of lanyard type, and is generally larger for stiffer ropes. This was based on the comparison between rigid test weight and anthropomorphic, articulated dummy. A range of vertical lifeline based FAS were also tested, which showed that C varied with FAS type, but was nearer to 1 than the previously thought value of 2 [pp 33-43].

• Other work in determining a value for C was for the basis of determining arrest force by calculation, using a mathematical formula instead of drop-testing. Also, because of the dangers in using human volunteers in testing, and because of the difficulties in extrapolating results from test surrogates to human beings, C was redefined as the factor between a test weight and full, anthropomorphic, articulated dummy. This value was determined to be near enough 1 when drop-testing using a full body harness as the containment device. However, still other test work has shown that C does vary according to type of FAS, and that it can vary from between 1.15 and 1.25. This is based on the rigid test weight and anthropomorphic, articulated dummy comparison [pp 41-43].

• Providing that drop-test methods are well thought out and are reproducible, and that instrumentation is calibrated frequently during extensive testing, use of more complex test surrogates such as anthropomorphic, articulated dummies do not necessarily lead to test results with a low degree of repeatability [p 43].
Work in other impact biomechanics fields has also been conducted to determine restraint loads in different kinds of surrogate. In the vehicle crash protection field, it has been shown that restraint loads in frontal impact scenarios decrease as sophistication in surrogate increases. Ratios of 2.3 : 1 for rigid wooden torso type surrogates, without head and limbs and 1.3 : 1 for highly specified anthropomorphic, articulated dummies have been demonstrated, as when compared to restraint loads on humans in similar test circumstances [pp 43-46].

Whereas initial research in the vehicle crash protection industry sought to produce simple and inexpensive test surrogates for repetitive crash testing, the trend reversed as more and more degrees of sophistication were applied to a range of crash test dummies, in order to produce a greater degree of realism and reproducibility [pp 45-46].

It would appear that a large number of fall-arrest researchers have used anthropomorphic, articulated dummies for drop-test purposes, but these have been borrowed from other impact biomechanics industries, particularly the vehicle crash protection industry. This may cause inaccuracies in test results, and may lead to damage, as most dummies appear to be designed for loading and response in one plane of motion only. It would appear that little research has been conducted to produce a dummy specifically for fall-arrest purposes. It would also appear, at the time of writing, that there are no available dummies which are capable of being used accurately for dynamic response purposes in omni-directional tests, as that required in fall-arrest conditions [p 46].

Some researchers propose that an anthropomorphic, articulated dummy should be used for assessing the performance of safety harnesses, whilst a heavier rigid torso shape can be used for a dynamic strength test. Some argue that a range of tests are required to assess safety harnesses, since there is not one test on its own that can assess all of the factors involved; none on their own give the complete answer to the problem of body containment in a FAS. Such a range includes the use of humans, full dummies and torso dummies. The use of humans is valid in slow lifting and suspension tests; the use of full dummies is valid for performance tests; and the use of torso type shapes are valid for strength tests. This was the philosophy originally adopted in the new international standard ISO 10333-1 (2000) and draft international standard ISO/CD 10333-6 (2000) [pp 46-49].

There are limitations and factors with the various types of surrogate which have to be weighed up when a selection of a surrogate has to be made. Acquisition and running costs are an important factor, and basically increase with increased degrees of surrogate sophistication. Similarly, costs associated with durability, repair and calibration tend to be higher as the degree of surrogate sophistication increases. Routine testing may just require simple, inexpensive tests, whereas safety critical testing may require more complex and therefore expensive tests. It depends on what attribute is being targeted for assessment [pp 49-52].

Pendulum head-first, feet-first, and horizontal trajectory drop-tests have been conducted on anthropomorphic, articulated manikins of 77 kg at pendulum pre-release angles of up to 50º from the true vertical. The lanyard strangulation issue was assessed, but was not reproduced. Decelerations in the $-a_z$ direction of approximately 5g and in the $+a_x$ direction of approximately 10g were recorded at the chest [p 50].
• Some researchers assert that because manufacturers simply have to design safety equipment to pass tests in standards, standards need to be improved with more realistic tests if safety equipment is to improve in design and protection [p 51].

• There are cases where the testing of individual components of FAS have been satisfactory, because of the simplified form of testing, but where the same components have been brought together and tested in a more complicated fashion, reflecting their use, have resulted in test failures. Specific situations recorded are: tripod and retractable lifeline – (collapse of tripod), roof mounted anchor and retractable lifeline extracting and retracting horizontally – (shearing of line over edge), vertical rail and trolley – (inability to arrest dummy body due to incompatibility of components) [pp 27, 52].

• The rigid test weight, sand bag and rigid torso test surrogates cannot detect critical performance defects with FAS. These include potential severing of limbs and head, straps cutting into and pressurising the sides and back of neck, and garrotting of the neck. These kind of critical defects are usually only detectable with full anthropomorphic, articulated dummies, or in some cases by using static suspension methods with human volunteers [pp 16-17, 19, 53-57, 61].

• The degree of anthropometric representation of the EN 364 rigid torso is very limited and can only serve to be a shape suitable to fit into a harness. Its purposes are limited to strength testing only. Certain features of safety harnesses cannot be assessed using this surrogate [pp 53-57].

• The standard EN 361 (1992) allows failure of primary sewn joints providing that the torso surrogate is retained in the safety harness at a specified angle. This is potentially dangerous for the user. The standard assesses strength only, with no assessment of safety [p 55].

• The adoption of standards within the UK, such as EN 353-1, has produced a backward step in terms of safety and technology and has stifled future innovation. Previous UK standards tested ladder-installed vertical systems as a full system, with a full, anthropomorphic, articulated test dummy. The maximum arrest force allowed was 8 kN with a 1.5 m arrest distance. In practice most manufacturers were able to accomplish this readily without the need to use any form of energy dissipating device, enabling the connection between fall arrest device and worker to be relatively short. The adoption of EN 353-1 led to the need for energy absorbers to be fitted to fall-arrest devices, which leads to more difficult climbing and greater free falls. This is because a test weight is utilised instead of a full dummy, and consequently the energy dissipating qualities of the harness cannot be realised. This was exacerbated due to the maximum arrest force allowable being reduced from 8 to 6 kN [pp 60-61].

• Specifying a anthropomorphic, articulated dummy for fall-arrest purposes can be difficult, but agreements have been arrived at in the past where national standards making bodies have introduced such equipment into standards. Methods have also been trail blazed by other impact biomechanics industries that face the same problems. However, this has also led to the use of dummies of different sizes, where it has been realised that size could critically effect the outcome of the test in question [pp 61-64].
- Arrest forces are generally higher when drop-testing individual components with rigid test weights and sand bags, as compared when full systems are tested with a full dummy. This is because the interaction between components, the stretching of the safety harness and the flexing of the dummy all contribute to energy dissipation, as would happen in “man-fall” conditions. Depending upon free fall, an energy absorbing component may register up to 20% more arrest force when drop-tested on its own than when tested within a full FAS, under similar test conditions. Design and manufacture of energy-absorbing components may be hampered by testing that is far too onerous and not realistic [pp 34, 37-43, 60-61].

- The most important aspect of any FAS is that it must stop the fall of a worker before the fall allows the worker to collide with the ground or other substantial structure. This creates the need to know how much free space is needed to be underneath the worker, prior to any fall. This is much easier to determine when the FAS in question is tested as a full FAS. Otherwise, a calculation based on the arrest distance contribution of each of the components has to be performed. Some of these contributions have to be estimates, based on component performance tests, which may not be the same value as when tested together with other components [pp 58-59].
6. FUTURE RESEARCH DIRECTIONS AND RECOMMENDATIONS FOR FURTHER WORK

- Further investigation could be undertaken on drop-testing of different fall geometries, testing the most unfavourable fall trajectory in combination with the most unfavourable FAS.

- Further investigation could be undertaken to drop-test different types of safety harness using different harness attachment points on a range of different individuals/anthropomorphic dummies with different anthropometrics.

- Jolt measurement and tolerance criteria is a topic for future research in fall-arrest work, especially in localised and vulnerable regions of the body such as the neck and head.

- There is sufficient evidence to revisit and review the standard 6 kN limit. The parachute opening literature could be investigated further. Some limits of duration could be applied. Higher one time excursions could be allowed. Different levels of arrest force could be applied for different FAS. Thresholds could be expressed in terms of probability of injury, so no absolute value is estimated. Tolerance could be expressed in terms of acceleration instead of force, in line with other impact biomechanics fields. Thresholds could also be based on areas of the body rather than blanket approaches. Tolerances could also be specified in different directions/planes.

- The above work could lead to solutions for workers who are outside the “100 kg mass” criteria – ie thresholds could be acceleration orientated rather than force orientated.

- Methods could be investigated that assess safety harnesses in a more purposeful manner. Design and technology of safety harnesses could be improved.

- Standards such as EN 361 could be substantially improved to take into account human factors criteria. This could include the use of human volunteers for static suspension tests and anthropomorphic, articulated dummies for performance tests. Strangulation and garrotting tendencies could be assessed.

- Testing under man-fall conditions could be considered in standardisation procedures or in other codes to link actual practices with test methods. This could include pendulum, head-first and other trajectories. This may detect incompatibilities between components and how fall arrest capability is affected. Full system testing could be investigated from the viewpoint of making performance tests less onerous where it known that issues arise. Free space clearances could be recorded in system testing.

- Female impact tolerance and specific issues relating to female requirements for FAS could be researched.

- EN 353-1 could have more realistic system tests so that energy absorbers can be deleted from fall arresters. Present drop-test weight could be used in dynamic strength test, not dynamic performance test.

- Research could be conducted into the production of a dedicated fall-arrest full anthropomorphic, articulated dummy, acceptable to industry.
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8. APPENDIX:
HISTORICAL LINKS BETWEEN THE
ROYAL AIR FORCE INSTITUTE OF AVIATION MEDICINE
AND THE FALL-ARREST INDUSTRY

8.1 INTRODUCTION

Research already mentioned in this review in Reader (1969a), (1979) and in Beeton et al (1968), as conducted at the Royal Air Force Institute of Aviation Medicine (RAFIAM), based at the Royal Aircraft Establishment, Farnborough, along with an understanding that the RAFIAM had historical links with the fall-arrest industry, led the Author to search for further RAFIAM documents of primary importance to the review. Further documents (which hitherto were unavailable) were obtained with the kind permission of the Officer Commanding the Royal Air Force Centre of Aviation Medicine (RAFCAM) as currently designated, now based at Royal Air Force Henlow. This appendix reviews the additional material obtained.

In particular, the historical links between the RAFIAM and the fall-arrest industry are apparent from:

- Fairbairn (1980), which reports on a test programme commissioned via the British Standards Institution Committee PSS/5/2 as a means of checking the feasibility of chosen deceleration maxima for the fall-arrest of personnel wearing industrial safety belts or harnesses fitted with lanyards either with or without energy absorbers. The committee in question was responsible for the writing of fall-arrest equipment standards, e.g.: BS 1397 (1979). Fairbairn (1980) goes on to say that: “recommendations had previously been made to the BSI Committee PSS/5/2 by the Institute of Aviation Medicine, RAE, Farnborough, that personnel wearing abdominal belts should be subject to no more than 5g deceleration, whilst 10g is a safe upper limit when wearing a full harness”. The 5g and 10g criteria appear as performance requirements in the British Standard BS 1397 (1979).

- Reader (1969a), where research is conducted on industrial safety harnesses “for the protection of personnel against injury in the event of a fall when servicing large aircraft”.

- Stevens (1968) and Longrigg (1969) who refer to the Royal Aeronautical Establishment Public Open Days in June 1967, where “tear web” (a material used in current day fall-arrest energy-absorbing devices) was being demonstrated as a safety line using human subjects. The subjects, wearing a harness and connected by the tear web, were dropped over a distance of 2.75 m before being arrested. Two types of tear web were used, WR 1017 and WR 1018. Twenty-six demonstration drops were carried out with WR 1017 and twelve with WR 1018. WR 1017 applied an arrest force of between 2.6 – 3.6 kN and WR 1018 applied an arrest force of between 3.9 – 5.2 kN. These figures were the actuals recorded and are, therefore, not compensated for energy dissipated by the subjects and their harnesses. The mass of the subjects was not recorded.

- Crawford (2001), wherein the Author was informed that Wing Commanders Glaister and Reader were two RAFIAM experts who were regularly consulted by the National Engineering Laboratory (NEL), a leading body in the field of fall-arrest testing.
8.2 FALLS FROM AIRCRAFT WHILST IN FLIGHT

In Reader (1979) the particular design of a safety harness is described for crew members of fixed and rotary winged aircraft, who had a need to move around the inside of the aircraft. The design was to be integrated within a lifepreserver (inflatable lifejacket) and would be attached to an aircraft strong point by an adjustable strop. The report mentions comfort, compatibility and strength assessments conducted during static suspension and drop tests.

Reader (1979) describes the problems of preventing aircrew from falling out of aircraft in flight when they are moving around the inside of the aircraft, particularly when working near open doors, e.g.: a helicopter winchman performing a rescue. One existing method, the use of a waist belt attached by a strap to a fixed point inside the aircraft, is mentioned. Reference to Reader (1969a) is made, in which a review of industrial safety harnesses was undertaken (refer pages 15 and 16 of this report).

In this it was shown that a waist belt, although convenient to use, was a poor restraining device because in the event of a fall, high forces would be exerted on the abdomen with a considerable risk of internal injury. It is also asserted in Reader (1979) that a waist belt occupant could slip out of the belt inadvertently and, in the post-fall suspended position, with the body jackknifed about the waist and the means of attachment to the aircraft at the back of the body, Figure 20 refers, the crewman cannot get back into the aircraft.

![Figure 20: Post-fall suspension in an aircraft crewmember's waist belt. After Reader (1979)](image)
Two cases of such an incident are reported:

- During the Queen’s Review of 1968, a crewman fell from a Whirlwind helicopter and was suspended outside the aircraft and could not return until some time later (suspension time not recorded);

- In December 1970, a crewman fell from a Wessex helicopter and had to remain suspended below the helicopter until it landed (suspension time not recorded).

Furthermore, when so suspended, it was discovered that the body could rotate rapidly with the corresponding high risk of head and leg injury from impacts against the aircraft structure.

The waist belt at the time was made from natural materials such as cotton flax, which as reported in Reader (1979) was susceptible to ageing, rapid wear and contamination with grease. Also, the overall design only called for an ultimate strength of 9.7 kN and, the opinion in Reader (1979), was that premature failure could occur. Three serious military accidents are recounted from the 1966-1979 timeframe which involved the crewman’s waist belt (precise details withheld):

- Whirlwind helicopter crash October 1967. The crewman was restrained by the waist belt during the crash and suffered a fractured spine which, according to the medical staff who investigated the accident, was caused by a jackknifing-folding action of the body around the belt. All of the crew survived. No estimates or calculations of crash deceleration are given.

- Whirlwind helicopter crash June 1967. The waist belt failed in the crash and allowed the crewman to flail inside the cabin which led to fatal skull fracture and dismemberment. All of the crew drowned. Again, no estimates or calculations of crash deceleration are given.

- Whirlwind helicopter crash November 1969. The waist belt failed in the crash and the crewman was thrown from the aircraft and broke a collar bone. All of the crew survived. No estimates or calculations of crash deceleration are given.

8.2.1 New Body Containment Device

Reader (1979) asserts that an improved body containment device could have prevented the injuries reported in the first and third accidents above and could have altered the outcome of the second. Accordingly, a requirement for a new type of harness was issued. The main features specified were that should a fall occur the harness must:

- be able to arrest the fall as gently as possible, whilst holding the head erect;

- enable the suspended crewman to reach the strap connecting him to the aircraft and so be able to recover his position and re-enter the aircraft unaided.

The design consisted of a series of webbing straps sewn into a standard aircrew lifejacket which in itself was a garment enveloping the whole of the upper torso. The principle configuration of the straps was as such to encircle the torso and arm holes of the lifejacket, and to provide a self-tightening feature. It is also worth noting that the connecting hook, which would be used to connect the harness strop to the aircraft structure, had to feature a double-acting spring catch to prevent inadvertent disconnection and to be capable of being proof-loaded to 11 kN, both requirements under BS 1397 (1979).
When a fall-generated impact force was applied via the strop which connected the harness to the aircraft, the loops of webbing around each arm hole would tighten. This would hold the lifejacket closely around the upper torso, and would offer two main advantages:

- preventing the release of the occupant from a badly-adjusted lifejacket in a fall;
- distributing the arrest load over the whole upper torso.

During testing, it was noted that the tension around the chest, whilst causing mild discomfort, did not prevent breathing.

Reader (1979) goes on to mention that this particular design did not use straps between the legs as with industrial harnesses. The reasons given were that aircrew did not favour leg straps and probably would not use them if fitted. The unsupported claim is also made that the concept of the harness would be made more complex to use, and would be more injurious in the arrest of a fall, if leg straps were fitted.

A frangible stitching arrangement at the dorsal attachment point on the harness served two purposes. First, the frangible stitching arrangement held the self-tightening arm hole straps in the relaxed position, so that a crewman could lean out of an aircraft against the connecting strop without causing the self-tightening mechanism to come into play, but the arrangement would break and allow the arm hole straps to self-tighten in the event of a fall. The break figure was set to be around 0.7 kN. The second purpose was to indicate that arrest loadings had been imposed and that inspection or replacement of the harness would be necessary – a kind of “tell-tale” indicator.

8.2.2 Human Static Suspension Tests

A series of static suspension tests are then described in Reader (1979). Human subjects donned normal flying equipment plus the new lifejacket-harness and were winched off the ground by the strop which was connected to the harness attachment point. The frangible stitches were broken to allow the self-tightening arm-hole straps to purchase. The comfort and ease of movement and breathing were checked and the ability to grasp the suspension strop and simulate pulling oneself into an aircraft was assessed.

It was reported that, providing the waist strap of the lifejacket-harness was correctly adjusted, the comfort when suspended was acceptable. Subjects could also grasp the suspension strop (attached at the rear of the subject) and elevate themselves and control their movements, although this is not elaborated on and there are no photographs in the report which confirm this claim, which in the Author’s view is dubious. Certainly in the conclusions of Reader (1979) it is stated that the new safety harness “should permit unaided re-entry of the aircraft”, which in itself indicates that this aspect of the concept was not fully assessed.

Reader (1979) continues to report that if the waist adjustment was left too slack, the harness could rise up over the chest and impart high loads under the armpit and over the lower ribs – but this was judged acceptable in an emergency. No subject could wriggle out of the harness unless the adjustment was very slack. Trials were also conducted without any of the front lifejacket buttons fastened. Providing that the arms were not elevated, the lifejacket-harness did suspend the subjects solely at the armpits, but with some discomfort.

The discomfort caused by the lifejacket-harness suspension procedures was then compared with that caused by the waist-belt item which was in service at the time. Whatever the human subjects had experienced in the lifejacket-harness suspension tests, all judged suspension in the waist belt as almost intolerable.
All the body weight was borne by the abdomen and, despite correct adjustment, a large amount of slack appeared in the belt upon suspension, as seen from Figure 20, and this could permit the body to slide out. There was no possibility of grasping the suspension strop or re-entering the aircraft when suspended, and subjects tended to spin out of control about the main axis of the strop. Under all conditions, the lifejacket-harness was preferred to the waist belt.

8.2.3 Drop Tests Using Dummies

Reader (1979) goes on to describe a series of drop-tests using a full, articulated, anthropometric dummy “sized to approximate the 95th percentile male and weighing 107 kg”. No reference is made to what dimensions the 95th percentile alludes to, nor why 107 kg is chosen. Neither is the make of the dummy mentioned. The dummy was dressed as a crewman would dress, complete with lifejacket-harness.

The aircraft strop was connected to the harness and to a strong point in the laboratory roof. A strain gauge buckle was clipped to the strop “near the hook to measure tension loads in the strap of the safety harness”, so it is assumed that the loads were measured near to the harness as opposed to near the anchor point in the roof. The output from the strain gauge was sent via a flying lead to an amplifier and ultra violet light recorder. No details of the measuring electronics are given.

The dummy was then hoisted independently and was dropped so that the lifejacket-harness arrested the fall, so simulating a crewman falling from an aircraft. High speed cine photography was taken of the dummy’s trajectory.

The drop-test sequence started with a free fall of 1.0 m. Reader (1979) reports that “at this drop height with other harness assemblies, the velocity attained in the fall imposes a deceleration of approximately 10g on the dummy”. (It would be of interest to this review to determine what the “other harness assemblies were”, but the reference may allude to parachute opening simulations as described earlier in Beeton et al (1968) where Reader was one of the joint investigators. Reader (1979) continues: “However with the lifejacket harness, a free fall of 1.14 m produced a peak arrest load of 5.6 kN, equating to a deceleration of only 5.3g”. It was noted that the lifejacket-harness rose up over the dummy’s chest until fully arrested by the armpit straps and the self-tensioning of the assembly around the chest. It was claimed that these relative movements reduced the expected loads because the deceleration pulse time and distance were effectively increased.

It was also claimed that the addition of straps around the legs would have made the harness more uncomfortable and would have increased the arrest load. However, no evidence is offered for this and, unusually for RAFIAM tests of this nature, no tests were conducted with human subjects. Perhaps Reader was referring to previous work in Norris and Lamont-Smith (1965)? In this, the parachute harness leg straps of an aircraft’s ejection escape system were found to produce unacceptable levels of crutch pain in static suspension and in drop tests with human subjects.

Reader (1979) then goes on to comment that “safety harnesses are usually tested to 10g for strength” and so further drop tests were proposed with increased free fall height in order to obtain higher deceleration figures. This statement seems to be at odds with the recommendations given to the BSI Committee PSS/5/2 by the RAFIAM as reported in Fairbairn (1980), as mentioned in page 83 of this report. In this, the deceleration of 10g is presented as a safe upper limit of human tolerance to impact deceleration, whereas in Reader (1979) the deceleration of 10g seems to be presented as a harness strength test.
However in other RAFIAM papers, which describe drop-tests using human subjects to simulate the man-seat separation and parachute deployment sequence of emergency aircraft ejection, the deceleration of 10g is seen as an expected operational load, i.e. both pilot and equipment would be expected to sustain loadings generated by a 10g deceleration, Ernsting (1967) and Reader (1967).

Further dummy-based drop-tests are described in Reader (1979) which escalate in terms of free fall drop height. A free fall of 1.5 m realised a peak arrest loading of 6 kN, equating to a maximum deceleration of 5.7g, based on the dummy’s total mass of 107 kg. Similarly, free falls of 2.0 m and 3.0 m realised peak arrest loadings of 7.4 kN and 10 kN and maximum decelerations of 7g and 9.5g respectively.

Reader (1979) points out that the majority of tests were more severe than that would occur in service, as the strop which connected the lifejacket-harness to the aircraft would only permit a free fall of 1.0 m. Accordingly, the 2.0 m and 3.0 m drop tests indicated that there was a considerable reserve of strength in the lifejacket-harness. The 2.0 m and 3.0 m drop tests appear to be a type of dynamic strength test, i.e. they subjected the equipment to twice and thrice the amount of fall-energy expected in practice. It is interesting to note that in BS 1397 (1979) the overload test for a harness was conducted with a free fall drop of 3.0 m, although there may be no connection with the RAFIAM tests.

Finally, an interesting point of historical note is made. Reader (1979) suggests that if the fall arrest forces were needed to be cushioned further then “ply-tear” webbing could be utilised in the lifejacket-harness. This is the tear-web material commonly used in the energy-absorber packs of today, commonly seen integrated within lanyards for fall-arrest use, but originally developed at the Royal Aircraft Establishment at Farnborough, for a variety of uses, Stevens (1968) and Longrigg (1969).

8.3 DROP TESTS SIMULATING PARACHUTE OPENING SHOCK

In Reader (1970) a combined harness is described which when fitted to an aircraft ejection seat provides restraint to a pilot during crash deceleration, but also supports the pilot during a parachute descent. In a parachute descent, the parachute canopy inflates after the pilot and ejection seat are fired from the aircraft, then the pilot and seat become separated, and deceleration is applied by the parachute and harness to the pilot so that a safe descent and landing may be made. Reader (1970) points out that the airspeed of a falling body at terminal velocity* is in inverse proportion to the square root of the local air density, so that parachute deceleration applied increases with altitude, and that the speed of inflation of the parachute is approximately proportional to its true airspeed. These factors mean that there is an altitude above which parachutes must not be opened, or else damage could occur to either pilot, harness or parachute.

Reader (1970) describes an accident in which a high speed high-altitude aircraft ejection took place, where the stitches connecting the crutch straps to the buttock sling of the harness had failed, causing separation of pilot from harness. Reader (1970) goes on to claim that no tests had ever been conducted to determine the strength of, nor the distribution of loads in, the harness under the conditions of parachute inflation.

* the constant maximum velocity reached by a falling body – no further acceleration takes place as the force of gravity is balanced by the force of air resistance.
Reader (1970) proceeds to describe the basic configuration of the harness, which is worth recording here since fall-arrest harnesses have a clear lineage back to parachute harnesses. In particular, Reader (1970) records how the buttock strap carries the load from the two back riser straps to support the occupant. To ensure that the buttock strap does not become displaced and allow the occupant to fall out of the harness, two leg loops are attached to the centre point of the buttock strap. These leg loops pass through the crutch area and fasten through metal “D” rings on the lap straps (Figure 21).

Figure 21 – Seat mounted combined harness configuration after Reader (1970)
In proceeding to describe the method of test, Reader (1970) records that the distribution of forces in the parachute harness was to be determined by means of drop-tests using a Sierra Engineering Company anthropomorphic dummy (Sierra “Stan”), as mentioned elsewhere in this review, e.g. pp 36 and 46. Reader (1970) describes this test surrogate as “built to 50th percentile weight, weight distribution and size, and is fully articulated”. The dummy was dressed in full flying gear which included the parachute harness. The parachute was disconnected from the harness and the riser straps, which, whilst normally connect to the parachute, were instead connected to two steel cables attached to a joist within the laboratory roof (Figure 22). The harnessed dummy was then raised by a mechanical winch attached to a bomb release to a sling around the dummy’s buttocks, so that the parachute riser straps became slack (lower view of Figure 22). To simulate the forces of parachute inflation, the bomb release was opened and the dummy allowed to fall until arrested by the tension of the parachute riser straps and steel cables.

In order to provide a series of measurements over a wide range of accelerations, the dropping height was increased in steps until the maximum force that could be imposed on the overhead joist was reached. The forces produced in the riser straps and harness straps by the drop tests were measured by strain gauges. Strain gauge buckles were clipped onto each parachute riser strap, each leg loop strap, one on a front shoulder strap and one on a rear shoulder strap. The outputs of the strain gauges were led to bridge amplifiers and then to galvanometers of a six channel ultra-violet light recorder. The strain gauges were calibrated before the experiment by means of a Hounsfield tensometer. After each drop test, the dummy and harness were examined for damage and the harness adjusted if necessary.

Interestingly, all of the harnesses used in the tests had been used previously in service. One had been used in a previous ejection but was undamaged. The others had been used continuously either in front-line service or during flight trials.

The results obtained are shown in Table 6. The loads measured in the various components of the harness and the peak deceleration are tabulated for each drop. The weight of the dummy and its worn equipment was 93 kg (indicating that the worn equipment had a mass of 19.5 kg). In order to calculate the deceleration imposed, the loads in the two parachute riser straps were added together and then divided by the weight of the dummy and associated equipment, a method confirmed by others in drop-testing e.g. Birchenough (1979).

In reviewing the strap loads, Reader (1970) states that the average percentage of the total load imposed on the leg straps was 27%, 31% and 9%, reflecting the 3 types of harness tested (Mk 26, Mk 43 and Mk 10). The front shoulder strap carried higher loads than the rear strap. The left front shoulder strap of the Mk 26 harness bore an average load of 38% of the total load, whilst for the Mk 43 harness the corresponding figure was 35%. The right back shoulder strap of the Mk 26 bore an average load of 16% of the total load, whilst for the Mk 43 this was 24%.

The loads imposed on the strain gauge buckles closely approached their ultimate strength and some failures did occur. This explains why some readings are not present in the table. The maximum deceleration achieved on the Mk 43 harness was 20g. Reader (1970) records that the rate of onset was 214 g/s with a 125 ms duration, but no impulse curves are shown. Loads in the leg loops did not exceed 3.5 kN and at no time did failure of the harness occur.
Figure 22 - Upper view: Sierra Stan dummy being winched up in preparation for drop-test to simulate parachute-opening snatch loading.

Lower view: riser straps slack and dummy ready for release. After Reader (1970)
### Table 6

Drop test results simulating parachute opening snatch with Sierra Stan dummy in harness.

After Reader (1970)

<table>
<thead>
<tr>
<th>Harness Type</th>
<th>Free fall (m)</th>
<th>Deceleration (g)</th>
<th>Measured Strap Loads (kN)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>L riser</td>
<td>R riser</td>
<td>LF shoulder</td>
<td>RB shoulder</td>
<td>L leg</td>
<td>R leg</td>
<td></td>
</tr>
<tr>
<td>Mk 26</td>
<td>0.3</td>
<td>4.5</td>
<td>3.16</td>
<td>0.93</td>
<td>1.67</td>
<td>0.42</td>
<td>0.81</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>10.6</td>
<td>5.54</td>
<td>4.19</td>
<td>3.27</td>
<td>1.62</td>
<td>1.52</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>13.3</td>
<td>7.16</td>
<td>5.07</td>
<td>4.24</td>
<td>2.02</td>
<td>2.02</td>
<td>1.13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>16.1</td>
<td>8.39</td>
<td>6.34</td>
<td>5.23</td>
<td>2.71</td>
<td>2.59</td>
<td>1.55</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>19.7</td>
<td>9.88</td>
<td>8.18</td>
<td>8.08</td>
<td>3.78</td>
<td>2.85</td>
<td>2.44</td>
<td></td>
</tr>
<tr>
<td>Mk 43</td>
<td>0.3</td>
<td>5.8</td>
<td>2.69</td>
<td>2.63</td>
<td>1.69</td>
<td>0.89</td>
<td>0.82</td>
<td>0.69</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>7.4</td>
<td>2.6</td>
<td>4.23</td>
<td>3.05</td>
<td>1.62</td>
<td>1.45</td>
<td>1.13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>12.1</td>
<td>5.38</td>
<td>5.43</td>
<td>3.2</td>
<td>2.58</td>
<td>1.96</td>
<td>1.56</td>
<td></td>
</tr>
<tr>
<td>Mk 10</td>
<td>1.2</td>
<td>15</td>
<td>7.03</td>
<td>6.72</td>
<td>5.05</td>
<td>3.45</td>
<td>2.89</td>
<td>2.85</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>18.5</td>
<td>8.41</td>
<td>8.54</td>
<td>5.56</td>
<td>4.45</td>
<td>2.96</td>
<td>2.36</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>-</td>
<td>7.52</td>
<td>-</td>
<td>-</td>
<td>3.67</td>
<td>1.82</td>
<td>1.94</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.8</td>
<td>20.1</td>
<td>8.8</td>
<td>9.66</td>
<td>5.92</td>
<td>5.9</td>
<td>3.32</td>
<td>2.67</td>
<td></td>
</tr>
<tr>
<td>Mk 10</td>
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<td>7.4</td>
<td>3.07</td>
<td>4.14</td>
<td>-</td>
<td>-</td>
<td>0.31</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>13.7</td>
<td>5.87</td>
<td>6.99</td>
<td>-</td>
<td>-</td>
<td>0.16</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>14.2</td>
<td>6.01</td>
<td>7.03</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>0.76</td>
<td></td>
</tr>
</tbody>
</table>

Note: LF – Left Front
      RB – Right Back

Some pulling of stitches was observed but none were broken. The loads in the leg loops of the Mk 10 harness were much lower; they did not exceed 1 kN at nearly 14g.

Reader (1970) concludes that, under conditions simulating parachute inflation, approximately 30% of the total load is imposed on the leg loops and 35-40% is imposed on the left front shoulder strap of the Mk 26 or 43 parachute harness. Also, decelerations of up to 20g did not
produce failure of any kind in the harnesses tested. It was felt that testing involving greater
deceleration should be conducted elsewhere to determine when failure would occur.

8.3.1 Parachute Opening Drop Tests using Human Subjects

In Ernsting (1967) a series of drop tests using human subjects are described. The tests were
designed to simulate the effects of man-seat separation and parachute deployment during the
ejection sequence from an aircraft.

The tests were called for as a result of RAFIAM modifications to the parachute harness and
lifejacket for the RAF’s Phantom aircraft. Development work had produced a combined
parachute harness and lifejacket closing fastener. Previously, the parachute harness had a
separate chest mounted closing buckle to the lifejacket. Drop tests conducted with human
subjects using this arrangement had caused bruising of the chest.

Three subjects were used who had a range of stature height of between 1.7 - 1.8 m, and mass of
between 65.8 – 77.1 kg. The sudden deceleration designed to simulate the snatch load imposed
by the deployment of the main parachute was produced by dropping each subject feet-first
through a known distance and arresting the fall by means of a pair of riser straps emanating
from the parachute harness. Each strap consisted of a 965 mm length of 45 mm wide webbing
and steel hawser.

Wearing full flying gear, the subject was first suspended by the pair of straps, then lifted up by
1.2 m, so to produce a deceleration of the order of 10g. The load in each riser strap was recorded
in some of the tests using a strain gauge link, bridge amplifiers and an ultra-violet light
galvanometer. The behaviour of the subject and the equipment during the tests was recorded on
high speed cine film.

Ernsting (1967) records 11 drop tests with human beings producing maximum decelerations of
between 9 – 10g. Durations and jolts are not recorded and the impulse curves are not shown. In
no case did the subject suffer any more than slight discomfort. When this did occur it was
experienced as slight pressure into the crutch caused by the leg straps, or over the upper parts of
the leg.

It was concluded in Ernsting (1967) that the combined parachute harness and lifejacket closing
fastener had caused the decelerative loadings to be more evenly distributed over the chest.
However, the need for vigilance in regard to strap kinematics comes to the fore from Ernsting
(1967) as in other parts of this review, e.g. p.16. It was highlighted that the combined closing
fastener could rise due to the tension in harness straps and could present a risk of damage to the
head or neck. This came from one test (with the smallest and lightest subject) where it had been
noted that the fastener was only 50 mm away from the chin in post-drop suspension. This led to
a modification to reduce the overall length of the fastener.

8.3.2 Asymmetric Drop Tests

Further work on the combined parachute harness and lifejacket in its modified state is described
in Reader (1967). Drop tests using human subjects were performed in a similar manner as
described in Ernsting (1967). The free fall heights were varied to produce different decelerations
and forces were measured at the two riser strap connections at the harness, together with the
force across the harness closing fastener which was mounted near the sternum. A total of 13
drop tests are recorded, with drops 10-13 being asymmetric in nature. These tests were arrested
asymmetrically mainly by the right hand riser strap attached to the shoulder part of the harness,
to simulate an awkward man-seat separation. Subject mass, including full flying gear, ranged
between 90.7 to 93 kg. A summary of results is shown in Table 7. Tests 3, 4 and 9 applied 8.8-
9g to human subjects in feet first drops when connected into a parachute harness and attached to the test structure by two shoulder mounted riser straps.

Corresponding arrest forces varied between 7.8 - 8.05 kN for these decelerations, with two of the subjects reporting “no discomfort” and one subject reporting “uncomfortable”. Figure 23 shows an impulse trace (from test 1).

Key: Traces 1, 2 and 3 correspond to forces (in imperial pounds) measured at the closing fastener.

Traces 4 and 5 correspond to forces (in imperial pounds) measured at the left and right shoulder positions respectively.

**Figure 23: Impulse traces from human drop test 1, simulating parachute opening and man-ejection seat separation in harness after Reader (1967)**
### Table 7
Human drop test results simulating parachute opening and man-ejection seat separation in harness after Reader (1967)

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Free fall (m)</th>
<th>Arrest force at shoulders (kN)</th>
<th>Force across closing fastener (kN)</th>
<th>Deceleration (g)</th>
<th>Subject’s comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Left</td>
<td>Right</td>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.3</td>
<td>1.34</td>
<td>1.35</td>
<td>2.7</td>
<td>0.23</td>
</tr>
<tr>
<td>2</td>
<td>0.6</td>
<td>1.6</td>
<td>3.4</td>
<td>5</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>0.9</td>
<td>3.9</td>
<td>3.9</td>
<td>7.8</td>
<td>0.3</td>
</tr>
<tr>
<td>4</td>
<td>1.2</td>
<td>4</td>
<td>3.95</td>
<td>8</td>
<td>0.32</td>
</tr>
<tr>
<td>5</td>
<td>0.15</td>
<td>1.1</td>
<td>1.5</td>
<td>2.6</td>
<td>0.14</td>
</tr>
<tr>
<td>6</td>
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<td>2</td>
<td>3.55</td>
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</tr>
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<td>7</td>
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<td>5.55</td>
<td>0.22</td>
</tr>
<tr>
<td>8</td>
<td>0.9</td>
<td>3.2</td>
<td>3.96</td>
<td>7.1</td>
<td>0.27</td>
</tr>
<tr>
<td>9</td>
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<td>4.6</td>
<td>8.05</td>
<td>0.33</td>
</tr>
<tr>
<td>10*</td>
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<td>0.8</td>
<td>2.1</td>
<td>2.9</td>
<td>0.39</td>
</tr>
<tr>
<td>11*</td>
<td>0.3</td>
<td>1.1</td>
<td>2.7</td>
<td>3.8</td>
<td>0.63</td>
</tr>
<tr>
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<td>2</td>
<td>3</td>
<td>5</td>
<td>0.71</td>
</tr>
<tr>
<td>13*</td>
<td>0.6</td>
<td>1.4</td>
<td>2.9</td>
<td>4.3</td>
<td>0.9</td>
</tr>
</tbody>
</table>

* asymmetric arrest
8.3.3 Suspension and Drop Tests in Parachute Harness

In Norris and Lamont-Smith (1965) investigations were undertaken to confirm reports that suspension in the parachute harness of the Lightning aircraft’s ejection escape system could produce unacceptable crutch pain. Six human subjects were involved with a test programme, which involved the wearing of full flying gear. The subjects were lifted into suspension, to simulate the body’s attitude when in a parachuting descent. They were kept in suspension for 8 minutes, and after 4 minutes the seat pack was released, to see if the weight of this made any difference to symptoms which the subject might have. After 8 minutes of suspension the subject was asked if they would agree to be dropped over a free fall height of 0.6 m into the harness.

A summary of results is shown in Table 8. Note that none of the subjects’ anthropometric measurements are recorded, neither is the arrest force in the 0.6 m drop tests. The results of the work in Norris and Lamont-Smith (1965) led to proposals for re-design of the harness strap configuration.
### Table 8

Human suspension and drop test results simulating parachute opening and descent after Norris and Lamont-Smith (1965)

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>In suspension</th>
<th>Effect of releasing seat pack</th>
<th>Effect of 0.6 m free fall drop test</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mild discomfort after 40s, still present after 2 mins. At 3.5 mins pain slightly worse due to swinging in riser straps but no increase beyond this.</td>
<td>none</td>
<td>none</td>
<td>some discomfort but acceptable</td>
</tr>
<tr>
<td>2</td>
<td>No discomfort on lift. Testicular pain after 3 mins. No relief obtained by manipulating webbing. Subject became pale and test terminated after 5 mins.</td>
<td>slight increase in pain</td>
<td>declined</td>
<td>severe testicular pain. unacceptable.</td>
</tr>
<tr>
<td>3</td>
<td>No discomfort on lift. Testicular pain after 1 min becoming severe. No relief obtained by manipulating webbing. Obtained some relief by squatting in harness and holding on to feet, was able to complete test.</td>
<td>none</td>
<td>declined</td>
<td>severe testicular pain. unacceptable.</td>
</tr>
<tr>
<td>4</td>
<td>Slight discomfort across back and buttocks, relieved by hanging on riser straps.</td>
<td>none</td>
<td>recent injury prevented test</td>
<td>no crutch discomfort but had testicular pain for two days following test</td>
</tr>
<tr>
<td>5</td>
<td>none</td>
<td>none</td>
<td>sharp stab of testicular pain on arrest</td>
<td>pain disappeared afterwards, but did not wish to repeat the drop test</td>
</tr>
<tr>
<td>6</td>
<td>none</td>
<td>none</td>
<td>none</td>
<td>comfortable throughout tests</td>
</tr>
</tbody>
</table>
8.3.4 Emergency Parachute Harness Drop Tests

In Reader (1969b) a new type of chest-mounted emergency parachute harness is evaluated, and one particular test involves the simulation of parachute deployment by drop testing human subjects. Loads which can be applied to the body via the harness and parachute riser straps were simulated by arresting the free fall of subjects wearing the harness by a pair of steel cables, attached at one end to the riser straps and at the other to a beam in the roof of the test area. Each riser strap contained a strain gauge link so that the load, and hence the decelerative force experienced by the subject, could be recorded using suitable amplifiers and an ultra-violet light galvanometer recorder. After donning the parachute harness, the subject sat in a sling which was attached to a hoist by means of a bomb release. The subject was lifted by the sling to a predetermined height and, after a warning, the bomb release was operated. The subject dropped until arrested by the tension in the parachute riser straps. The weight of the subject together with personal equipment and harness was recorded, so that the peak decelerative force could be calculated from the output of the strain gauge links. After the drop, the subject was questioned for comments on discomfort during the snatch load and subsequent suspension.

Anthropometric details of the subjects are recorded in Reader (1969b) and the test mass of the subjects ranges from 60.8 to 82.1 kg. A summary of results is shown in Table 9 wherein it can be seen that the maximum deceleration recorded was 9.9g, at an equivalent arrest force of 5.9 kN due to the subject’s mass. Reader (1969b) comments that: “there was some discomfort around the buttocks and groin on vertical acceleration but this was bearable, and did not limit subsequent suspension simulating a parachute descent”.
Table 9

Human drop test results simulating parachute opening with chest-mounted parachute harness after Reader (1969b)

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Free fall (m)</th>
<th>Deceleration (g)</th>
<th>Riser strap arrest force (kN)</th>
<th>Subject’s comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3</td>
<td>3.3</td>
<td>2.66</td>
<td>slight discomfort under buttocks and groin; lifejacket chafes armpits</td>
</tr>
<tr>
<td>2</td>
<td>0.6</td>
<td>6.2</td>
<td>4.99</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.1</td>
<td>9.0</td>
<td>7.25</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.3</td>
<td>-</td>
<td>-</td>
<td>slight discomfort under buttocks and groin; radio beacon pushed up to right armpit; canopy releases dig into shoulders</td>
</tr>
<tr>
<td>5</td>
<td>0.6</td>
<td>7.2</td>
<td>4.29</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.1</td>
<td>9.9</td>
<td>5.9</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.3</td>
<td>2.6</td>
<td>1.79</td>
<td>slight discomfort under buttocks and groin; radio beacon pressure; canopy releases dig into shoulders</td>
</tr>
<tr>
<td>8</td>
<td>0.6</td>
<td>5.0</td>
<td>3.45</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1.1</td>
<td>8.8</td>
<td>6.1</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.3</td>
<td>4.7</td>
<td>3.3</td>
<td>comfortable; lifejacket pushed up to armpits</td>
</tr>
<tr>
<td>11</td>
<td>0.6</td>
<td>7.2</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>1.1</td>
<td>8.5</td>
<td>6.0</td>
<td></td>
</tr>
</tbody>
</table>

Note: Tests 1-3 subject mass 82.1 kg
Tests 4-6 subject mass 60.8 kg
Tests 7-9 subject mass 70.3 kg
Tests 10-12 subject mass 72.1 kg

8.3.5 Parachute Drop Test Dummy

In Guignard (1961) the Royal Aeronautical Establishment’s prototype anthropomorphic parachute test dummy is described, and is tested to establish the dummy’s vertical response characteristics. It was considered that the dummy’s response to vertical sinusoidal vibration, if it should resemble that of a live man, would indicate whether the dummy provided a realistic dynamic simulation of the living figure.

The dummy was tested with the torso part separated from the legs at the hip joints and without the protective outer covering. The stiffness of the vertebral column (which could be adjusted by means of a tensioning rod passed axially through the stacked rubber and steel sandwiched
Guignard (1961) comments that “the dummy could barely sit erect without support and its tone resembled that of a cadaver”.

Sinusoidal vibration at a fixed double amplitude of 6.35 mm was applied vertically through the dummy’s pelvis. The frequency range of 1.4 to 9.5 Hz was applied in quarter-octave increments. The vertical acceleration amplitude was recorded at the root of the dummy’s neck and at the platen itself.

Seat to neck transmissibility – the ratio of amplitudes at the neck to those at the platen - was compared at different applied frequencies. An ill-defined resonance occurred at about 3 Hz, and upon post-test inspection it was suggested that this was due to torso flexion. There was also a possibility of a second resonance occurring at about 7 Hz which was associated with the axial compression of the spine.

Guignard (1961) concludes that the most noticeable feature of the dummy’s response was the absence of the large resonant peak at about 5 Hz which is the dominant feature of resonance curves that had been obtained from live men in Guignard’s previous work. Dynamically, the dummy bore a superficial resemblance to a live torso in flexion, but in its vertical response it could not be said to simulate the living subject at all closely. It was proposed that the dummy could be modified by incorporating into it an additional resonant mass tuned to 5 Hz.

8.4 CONCLUSIONS

The findings in this appendix generally support and reinforce the conclusions in the main report (Section 5) and the future research directions and recommendations for further work (Section 6).

There is a close correlation between body harness design, energy absorbing design and parachute-opening testing practice conducted at the RAFIAM during 1960-80, and that of corresponding practices within the fall-arrest industry. It would appear that fundamental design principles of fall-arrest full body harnesses have been driven largely by parachute harness technology and drop-testing methods.

It is also apparent that the establishment of human fall-arrest deceleration tolerance criteria owes its origin to the results of military parachute-opening tests using live subjects, but the reader should note that these pertain exclusively to feet-first fall trajectories with the body erect.

One significant difference appears to be that with parachute-opening simulations, the decelerative forces are shared equally and symmetrically via the parachute riser straps which attach at the two shoulder/upper chest points of the parachute harness, whereas in arrested-fall simulations the decelerative forces are transmitted to a single centrally disposed point either at the upper back or base of the sternum. However, in early fall-arrest full body harness design the arrest forces were transmitted to the full body harness as if it were a parachute harness, Reader (1969a), i.e. with the shock loading being shared equally and symmetrically at two shoulder/upper chest points on the harness. This matter needs to be carefully considered in any future deliberations.

There is certainly a case for the re-examination of this information in order that fall-arrest technology may be advanced for the benefit of safety when working at height, in line with the future research directions and recommendations for further work as listed in Section 6.