New Methods for Assessing Facial Injury Risk, Phase 1

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Abstract

New Methods for Assessing Facial Injury Risk, Phase 1

This report describes the first of two planned phases of a TRL project (11108286) to investigate new methods for assessing facial injury risk, by exploiting new and emerging technologies.

A literature review was conducted to establish the forces likely to be involved in facial fractures and thus identify the likely range of forces that any new methodology would need to be capable of measuring.

During the study a range of new and emerging technologies were assessed to identify their potential capability for measuring simulated facial injury forces. The assessment selected a distributed sensor fibre optic system which it is considered is worth investigating further.

A secondary project aim was to improve an existing "low test cost" mechanical impactor system. Although a possible improvement to the impactor system was identified, the cost of the associated consumables is considered too high to satisfy the "low test cost" requirement. For this reason it is not recommended that the mechanical impactor be developed further.

Executive Summary

New Methods for Assessing Facial Injury Risk, Phase 1

This report describes the first of two planned phases of a project to investigate new methods for assessing facial injury risk (other vulnerable body areas were also considered), by exploiting possibilities for new and emerging technologies.

TRL has a long term involvement in the development of impactors for assessing facial injuries. The existing system is based on the deformation of a honeycomb medium, which is crushed when fired at the object to be assessed. The force of the impact is assessed from the deformation of the honeycomb. Although this method is useful its practical application is difficult and therefore this project was set up to review alternative methods that could be employed, based on new and emerging technologies.

The potential applications for a new measuring system, were assessed and a number of potential markets identified, which include:

- Rail, buses & coaches, aircraft, other road vehicles, specialised off road vehicles, military vehicles, adapted vehicles, pedestrian head impacts, children's play areas.

Applications not included:

- Cars (because airbags have almost eliminated facial fractures in car crashes), boats, adventure park rides.

A literature review was conducted to review previous published research in this area and to establish the forces likely to be involved in facial fractures and thus identify the likely range of forces that any new methodology would need to be capable of measuring and withstanding.

During the study a range of new and emerging technologies were assessed to identify their potential, as equipment capable of measuring simulated facial injury forces.

The range of sensors investigated include:

- Distributed systems – fibre optic, laser, sensor skins, pressure mapping, 'carbon paper' (single use sensor films containing micro-encapsulated pigment and developer)
- Discrete systems – fibre optic, force sensors (including load cells)

The assessment selected a distributed sensor fibre optic system which it is considered is worth investigating further.

Recommendations

The following recommendations are made for a possible second phase:

- **Fibre optic system -** The most promising sensor system investigated was a distributed sensor fibre optic based system and it is recommended that its suitability be investigated further in a second phase of the project.
- **Mechanical impactor system -** A secondary project aim was to improve an existing "low test cost" mechanical impactor system. Although a possible improvement to the impactor system was identified, the cost of the associated consumables are considered too high to satisfy the "low test cost" requirement. For this reason it is not recommended that the mechanical impactor be developed further.

1 Introduction

The introduction of seat-belts and subsequently airbags in the modern vehicle fleet have dramatically reduced the numbers of fatal accidents on the roads. One reason for this is a reduction in the numbers of serious head injuries being sustained. However, as a result of accidents becoming more survivable, other, less serious, injuries have become a higher priority for prevention. Examples of injuries categorised as minor or moderate (AIS1 or 2) by the Abbreviated Injury scale are facial fractures, such as fractures of the nason or mandible, and soft tissue injuries to the abdomen. These injuries can have long associated recovery times and may be associated with some degree of disfigurement.

Although the introduction of airbags in cars has all but eliminated facial injuries in frontal car crashes, other forms of transport such as buses and trains still have the potential to cause such injuries. TRL has been involved in several projects to assess and improve secondary safety systems in both buses and trains. Currently, there is no standard facial injury detection device available and hence this project was commissioned to investigate available new sensor technologies.

Initially, a review of existing research on facial injuries was undertaken to determine the requirements for assessing facial injuries (such as injury tolerances and maximum loading conditions) and establish how new and innovative methodologies may be used to satisfy these requirements. The possible bases for such methodologies were then investigated, for further consideration in the event that a second phase were to follow.

2 Background

In 1985 TRL proposed a sub-systems test procedure for detecting facial injury risk for front seat occupants in frontal impacts to cars. The procedure was based on recording the localised deformation of an impactor made from close-packed aluminium honeycomb, dropped onto various locations on a steering wheel hub and rim. The procedure did not enter regulatory practice but was used, by consumer organisations, for a number of years to assess the risk of facial injury from steering wheels.

In recent years the use of airbags for both car drivers and front seat passengers has all but eliminated facial fractures for front seat car occupants and has diminished the risk of serious brain injuries (Owen and Hynd, 2001).

Although car occupants are now relatively well protected from facial injury, other modes of transport may still have a relatively high risk of facial injury associated with them, particularly in situations where the occupant is unrestrained or is only restrained by lower body restraints, such as a lap-belt. Recent rail industry testing at TRL has shown that a lack of restraint system use, coupled with the variety of impact surfaces, could pose a risk of serious facial injury to seated rail travellers. This risk could also apply to unrestrained bus passengers.

Technologies appropriate for assessing facial injury risk may be based on detecting localised force, pressure or deflection. It is likely that such technology may also have applications for detecting injury risks to other body regions. 'Knee pocketing' injuries (when the knee impacts the dashboard and becomes trapped) may also be detectable using such technologies. A recent project considered the risk of injury to child passengers on buses, restrained using adult seat belts alone, and found there was a risk of serious neck and abdominal injury (Grant *et al.*, 2005). The fact that children's physiology causes them to be improperly restrained by an adult belt implies that there is a need to produce a device to detect abdominal injury in both children and adults. Abdominal injuries are still an issue for adult occupants in frontal impact car accidents, particularly in rear seating positions.

If a suitable device for detecting localised loads could be developed it would have applications for injury detection for several body regions exposed to localised loading. For example, safety testing of disabled driver controls, public transport and leisure applications and so forth.

In order to maximise the likelihood of producing a scientifically robust device and test procedure, consideration should be given to its application. In this instance, the most likely applications for any device and procedure would be regulation and consumer testing to reduce the risk of injury. It is usual for a device selected for use in a regulatory test environment to meet the following requirements:

1. Have appropriate anthropometry to the population group most at risk or most likely to be involved in a particular accident scenario;
2. Have appropriate biofidelity, in terms of its motion during impact and its interaction with the test environment;
3. Have appropriate sensors (electrical or mechanical);
4. Provide a response that is both repeatable and reproducible;
5. Be capable of withstanding the impact conditions to which it is to be subjected without failure of either mechanical parts or sensors;
6. Have appropriate injury criteria and risk functions;
7. Be cost effective.

The focus for this phase of the project was on identifying and investigating suitable sensor and engineering technologies. At this stage, only items 3, 4, 5 and 7 were applicable to the specification.

3 Potential Applications for Facial Injury Detection Technology

The table below summarises the potential applications for facial injury detection technologies that were considered during the study and indicates those that may have a current or future test market.

Potential Application	**Potential test market (Yes/ No)**	**Comments**
Cars	*No*	*Research shows that facial injuries in cars has been dramatically reduced with the introduction of airbags.*
Rail	Yes	TRL has already received enquires for a suitable test procedure.
Bus & coaches	Yes	It would be more difficult to fit airbags in buses and coaches than in cars.
Boats	*No*	*Involves lower speeds than vehicle impacts and other types of potential accidents are considered to have higher risks.*
Aircraft	Possible	Facial impacts with furniture in front of seated passengers considered likely in an accident.
Other road vehicles	Yes	Including ambulances and fire engines. A number of initiatives currently under way, which would benefit from a suitable test procedure.
Specialised off road vehicles	Yes	e.g. quarry vehicles. Small market possible.
Military vehicles	Yes	Vehicles tend to be primarily designed for operational requirements. A suitable test procedure could be used to reduce injury risk in normal or impact situations.
Adapted vehicles	Yes	The disabled motorist market. Testing and modifications could minimise the risk associated with adapted equipment.
Pedestrian impacts	Yes	Potential for lower impact severity tests.
Home & leisure	Possible	There are in the region of 28,000 head and facial injuries in the home each year. Further analysis would be required to evaluate whether there are any trends which could be addressed.
Childrens play areas	Yes	It is possible there is scope to develop the application of face form technology but this area requires further investigation, beyond the scope of the current project.
Adventure park rides	*No*	*There is unlikely to be any potential to apply facial injury risk assessment to high speed adventure park type rides.*

Table 3.1.1 Summary of Potential Applications

3.1 Vehicle Applications

In this section a range of feasible vehicle applications are identified and their potential for the application of a facial injury detection system discussed.

3.1.1 Cars

Accident research shows that facial injuries in cars have been dramatically reduced since the introduction of airbags (Owen & Hynd, 2001). Hence, the potential market for a facial injury risk assessment test procedure is minimal.

3.1.2 Rail Industry and Applications to Buses and Coaches

One of the most obvious applications for facial injury detection technology is the rail industry. Secondary safety systems for train carriages are in their infancy and it is clear that facial injuries can occur in rail crashes. TRL is currently working in the area of improved secondary safety with the Rail Standards Safety Board (RSSB), who have commissioned much research that should lead to improved standards.

It should be noted that as there are rarely any restraint systems in place on current trains; occupants sustain a wide variety of injuries with considerable variation in injury mechanisms. However, from observations of tests carried out with dummies (restrained and unrestrained) head contacts with parts of the seat are observed (Figure 3.1.1) which would be likely to cause facial injury. The complex nature of rail crashes (impact, followed by derailment, followed by fire, for example) makes a simple proposal to improve secondary safety difficult. Thus there is a direct application for facial injury detection technology in this area of vehicle safety.

Unrestrained passengers in buses and coaches are similarly vulnerable to serious injury, although these crashes are not usually so complex. If seat belts were to become mandatory in buses and coaches it is likely that most of the more serious injuries would be mitigated. However, based on the experience of the introduction of seat belts in cars and the possibility that only lap-belts would be fitted to buses and coaches, occupants could still receive facial injuries in a crash, due to contact with the seat in front or other hard contacts such as hand rails. In these vehicles, the problem could not be alleviated by simply fitting airbags due to the cost and complexity associated with them.

Currently there is a lack of a suitable injury risk assessment test procedure with appropriate injury criteria for this application. In fact, there is little data on the injuries sustained in rail accidents or how the fracture tolerance data gathered for steering wheel impacts relates to injuries sustained as a result of rail and bus crashes.

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Figure 3.1.1: Moment of impact between passenger face and the seat in front impact as may be experienced in a bus or train seat impact.

3.1.3 Boats

Boating accidents take a different form to those of other vehicles in that road and rail vehicle accidents almost always involve an impact of some kind. Boating accidents may take the form of an impact, but this is less likely than other accidents such as capsizing, sinking, onboard fires, etc. Because of the nature of the boats in existence and the speed at which they are likely to travel it is less likely that facial injury detection technology would have an application here.

3.1.4 Aircraft

Aircraft occupants are generally restrained during higher risk periods but only by a lap-belt. Facial impacts with furniture in front of them are likely in the event of an accident e.g. when taxiing. A suitable procedure may have an application in this industry.

3.1.5 Other Road Vehicles

A number of initiatives are currently underway to improve passenger safety in emergency response vehicles such as ambulances and fire engines. These vehicles are not subject to the same secondary safety requirements as ordinary cars, vans and lorries. It is likely that passengers travelling in the rear of an ambulance could be susceptible to a variety of injuries were the vehicle to crash or move violently. A suitable procedure may have an application in these industries.

3.1.6 Specialised Off-Road Vehicles

TRL has been involved in a number of research projects with specialised vehicles e.g. quarry vehicles. A basic review of these types of vehicles showed that improvements could be made if impact considerations were taken into account, probably for minimal or no cost at the point of manufacture.

3.1.7 Military Vehicles

Military vehicles are primarily designed with operational requirement in mind. Examination of such vehicles shows that serious injury could occur if the occupant's head impacted structures around the vehicle interior. It is suggested that injury risk could be reduced by appropriate design (not compromising operations requirements or increasing costs) if appropriate assessment systems were to be available.

3.1.8 Adapted Vehicles

Cars are often adapted for use by disabled motorists but consideration is not always given to the potential of such modifications to cause harm in a crash. One typical modification is a handle attached to the steering wheel, pointing towards the driver, to allow the wheel to be turned with one hand.

3.2 Pedestrian Head Impact Applications

Pedestrian impact injury risk (in road traffic accidents), in terms of head contacts, is primarily assessed for brain injury. Facial injuries could occur at much lower impact severities and be much more frequent but these are not currently evaluated, probably due to the lack of appropriate accident data.

3.3 Home and Leisure Applications

RoSPA (Royal Society for the Prevention of Accidents) and the HSE (Health and Safety Executive) collect data every year on injuries sustained a variety of circumstances (including the home, travel, leisure activities, school, etc) from extrapolated hospital data. The data collected is very general but can indicate the magnitude of particular injury problems. Table 3.3.1, generated from the RoSPA web site (RoSPA, 2005) indicates the number of head and facial injuries sustained in a given year. The current database structure does not differentiate between head and facial injuries or identify the injury severity or cause. Hence this may not indicate a facial injury problem and considerable further analysis is required before any potential application can be identified in this area.

Year	No of Head/Face fractures
2000	29,271
2001	29,042
2002	27,019

Table 3.3.1: Number of head/face fractures in the UK sustained in home and leisure activities

3.3.1 Children's Play Areas

RoSPA inspect play areas on a regular basis and give awards to local councils regarding safety, accessibility, etc. The legal implications of these inspections are covered under the Health and Safety at Work Act.

Although playground safety has improved considerably over the last 20-30 years, accidents resulting in a hospital visit are still common, with approximately 40,000 per annum (RoSPA, 2005). It is possible there is scope to develop the application of face form technology, but this area requires further investigation beyond the scope of the current project.

3.3.2 Adventure Park Rides

There is unlikely to be any potential to apply facial injury risk assessment to high speed adventure park type rides.

TRL looked at this activity in 2003 and initially concluded that, apart from H&S procedures, the industry is widely self-regulated and has a very good safety record (in terms of accidents compared to rides taken). In the US, questions over the potential for brain injury were mostly put down to scare-mongering and electioneering. The view was that the most appropriate area for TRL's potential involvement would be in input for design, but this is a very high-tech and competitive market (and mostly in the US).

3.4 Other Considerations

The previous sections have outlined situations where facial injures are thought to be likely or known to occur. At the moment the only regulatory assessment of head injury is based on global head acceleration as assessed by the Head Injury Criterion (HIC), using test dummies or headform impactors (dummy heads or spherical surrogates), neither of which are able to assess the injury types being considered within the scope of this project. HIC may be a valid assessment of some types of head injury risk, but it does not evaluate the less life threatening or cosmetic type injuries which can have long term outcomes (e.g. disfigurement). No regulatory test procedure, complex or simple, is known of by which facial fracture and disfigurement can be assessed.

Most injury mitigation strategies, in automotive terms, are focused on the reduction of 'threat to life' injury as graded by the Abbreviated Injury Scale (AIS). For the face most of the injuries are graded as minor, AIS 1, or moderate, AIS 2, but this does not assess disfigurement or long term cosmetic consequences. This dimension to facial injury has not been investigated and quantified.

Many of the potential applications listed previously may not be supported in an expensive test procedure but may be viable in a simple low cost test procedure, if one could be developed. This is particularly true in the modified disabled vehicle market which, in some instances, is often a low-volume cottage industry environment.

In the context of the TRF study, if appropriate technologies and methods can be identified they could be used in simple sub-system test procedures and with dummies in larger full-scale tests. Such technologies may also be appropriate for the detailed assessment of other body area contacts and injury risk assessments.

4 Literature Review of Previous Research in this Area

4.1 Previous Facial Injury Research

Most previous facial injury research was conducted between 1970 and 1995 and aimed at reducing facial fractures resulting from car accidents, prior to the introduction of airbags. (The mechanism of injury being primarily facial contact with the steering wheel for both restrained and unrestrained drivers.) As a result, most injury tolerance data has been generated using experimental techniques designed to replicate a facial contact with a steering wheel. Despite this, it may be assumed that the main applications for a new facial injury detection device would be in circumstances where there was facial contact with the interior surface of a vehicle at similar speeds and hence this data is still applicable for the identification of a suitable sensor. There is, however, a need for more specific, up-to-date facial fracture tolerance data in order to develop a suitable device fully.

A number of face-forms have been developed in the past, designed to detect facial injury in the scenario described above. These early designs may provide some useful ideas which will be applicable to a new facial injury detection device and hence the salient design points have been summarised.

4.1.1 Injury Tolerance Data

A number of different authors have documented tests designed to assess the fracture tolerance of the facial bones and commented on the influence of various factors on fracture tolerance. The various bones of the face have different fracture tolerances (Figure 4.1.1) and there are varying amounts of fracture tolerance data for each different bone. In addition the methods used to obtain the fracture tolerances vary somewhat. The available data has been collated in Table 4.1.1 and details of the methods used to generate this fracture tolerance data are listed below.

Swearingen (1965) – The author recreated actual car crashes using detailed accident data to simulate an impact with a representative piece of car interior with a dummy head and measuring the force.

Nahum *et al.* (1968) – The authors conducted Post Mortem Human Subject (PMHS) tests on ten specimens (four male, aged 70 to 81 years and six female, aged 55 to 71 years) using an impactor with a contact tip area of 1 square inch (645 mm^2), covered with a crushable nickel pad, 0.2 inches (5mm) thick of varying densities (9, 7 and 3% by weight). The impact velocity and mass of impactor were not specified. A number of different bones were impacted locally to generate fracture data.

Hodgson (1970) – The author subjected intact PMHS specimens to blunt facial impact and measured the forces required to fracture the bones of the face. Two different impactor forms were used; one with radius 1 inch (25.4 mm) the other 5/16 inch (7.9 mm), both 6.5 inches (165 mm) long and applied with longitudinal axis parallel to the sagittal plane. The impactor mass was 10 lb (4.54kg) and each impactor was dropped from heights of 5 inches (127 mm) and above. (Taken from Newman and Gallup, 1984).

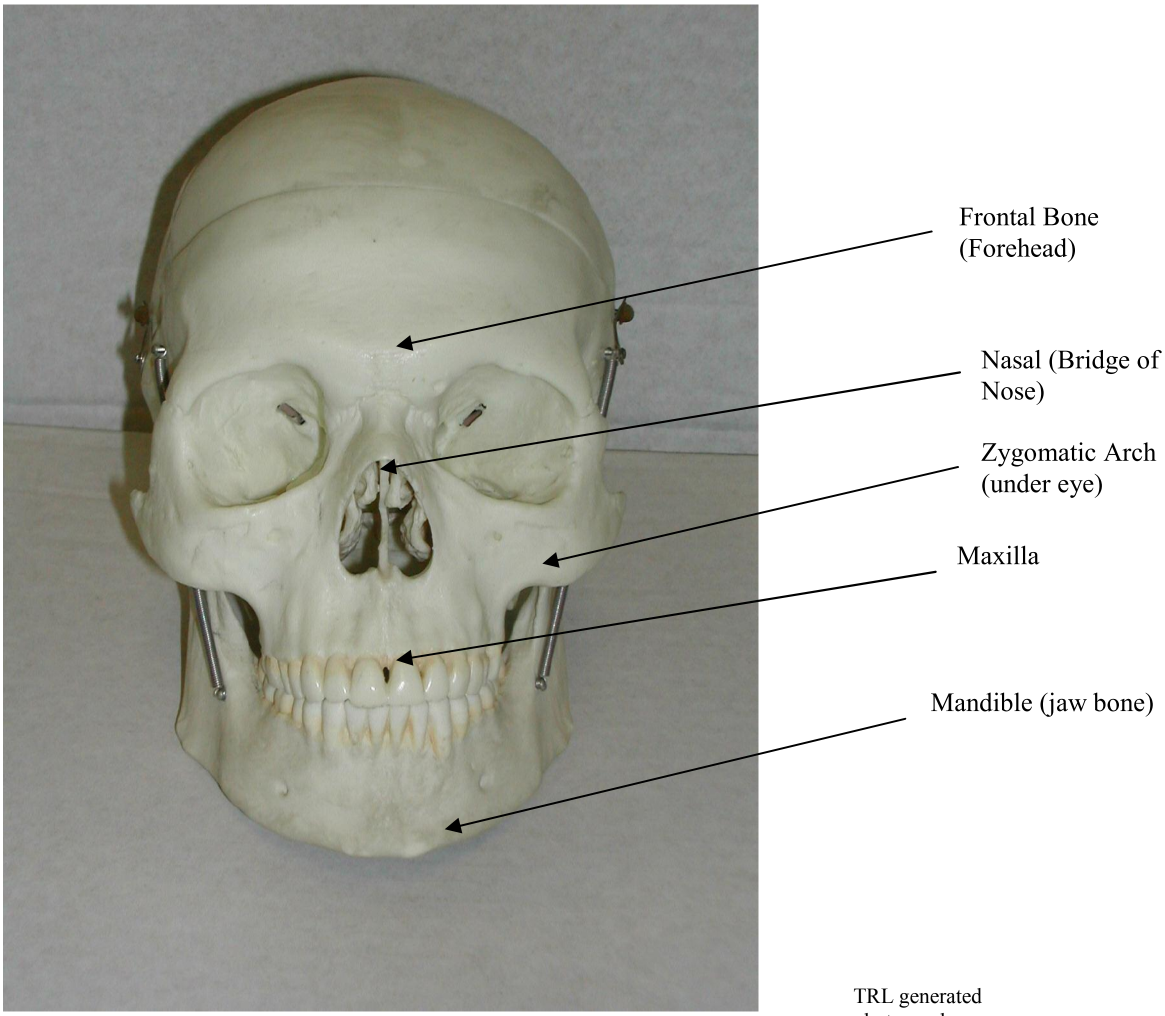
Schneider *et al.* (1972) – The authors used the same experimental technique as employed by Nahum *et al.* (1968), but extended the work to include the mandible and maxilla.

Nyquist *et al.* (1986) – The authors conducted PMHS tests with eleven subjects; four females, aged 43 to 57 years and seven males, aged 43 to 66 years. The impactor used had a mass of either 32 or 64 kg, depending on the test and consisted of a horizontal aluminium bar, diameter 25 mm, aligned with the bottom of the eye sockets on each subject. The impactor was propelled such that there was a small amount of constant velocity motion immediately prior to impact and impact velocities ranged from 10 to 26 $km.h^{-1}$ (2.8 to 7.2 $m.s^{-1}$). Impactor penetration and kinetic energy were measured. The applied force was estimated by recreating the impacts with a suitable dummy head and measuring the forces recorded. The authors concluded that impactor kinetic energy was related to fracture severity, but that penetration was not.

Allsop *et al.* (1988) – The authors conducted PMHS experiments by dropping an impactor onto a PMHS head to determine both fracture tolerances and bone stiffnesses.

Welbourne (1989) – The author used an impactor with a mass of 17 kg, fitted with a cylindrical steel bar of diameter 25 mm and an impact velocity range of 1-4 $m.s^{-1}$ to generate fractures in eight PMHS specimens aged 17 to 84 years. Both the impact force and kinetic energy of the impactor were measured. The tests were then recreated with a Hybrid III head with a frangible insert.

Yamada *et al.* (1970) - found little correlation between age and fracture tolerance, the difference between subjects aged 20-30 and 70-80 being only 20-30%. Gadd *et al.* (1968) suggested that the facial bones have less resistance to fracture in females than in males and that gender has a much more significant effect on fracture tolerance than age. Nahum *et al.* (1968) suggested that pressure may be more important than applied force in determining the fracture tolerance of the face, whilst Nyquist *et al*. (1986) and Allsop *et al.* (1988, 1991) have published force deflection data. Hodgson (1970) postulated that fracture tolerance was related to the time duration of the impact.



TRL generated photograph

Figure 4.1.1 Human Skull Model to Illustrate the Positions of the Main Bones of the Face

	Schneider and Nahum (1972) (J)	Schneider and Nahum (1972) (kN)	Swearingen (1965) (kN)	Nahum (1968) (kN)	Hodgson (1967) (kN)	Nyquist (1986) (kN)	Welbourne (1989) kN	Hodgson (1970) kN	Allsop *et al.* (1988) kN
Frontal Bone	37.3-56.0 (NF 56.0)	4.139-9.879 (NF 7.432)		4.005-4.895		1.174		5.473-5.607	2.201-6.494
Nasion			3.702				1.985		
Nose			1.388			0.343			
Maxilla	4.9-26.3 (NF 6.4)	0.623-2.003 (NF 1.202)		0.779-0.934	0.712	1.468	7.050 (?)		1.001-1.801
Zygoma	12.6-20.1 (NF 15.7)	0.979-2.848 (NF 1.914)		0.890-1.001 (NF 0.614)	1.602-2.136	0.489			0.889-2.402
Mandible	37.3-46.7 (NF 46.7)	1.891-4.116 (NF 4.005)		1.557-1.780		0.685			

Notes NF - highest recorded force for which no fracture occurred (kN)

- all impacting surfaces are approximately 1 square inch, unless otherwise stated

Table 4.1.1: Summary of Fracture Tolerances for the Bones of the Face (Newman *et al.*, 1984)

The EC FID Project (GRD1-1999-10559) considered fracture tolerance data for a number of different body regions and used data first proposed by Schneider and Nahum (1972) as listed in Table 4.1.2 in below.

Bone	Force Tolerance Level (kN)
Mandible (anterior-posterior)	1.78
Mandible (Lateral)	0.89
Maxilla	0.66
Zygomatic Arch	0.89
Frontal	4.00
Zygomatic Areas	0.89

Table 4.1.2: Fracture Tolerances for the Bones of the Face – Schneider and Nahum (1972)

The FID project also proposed biofidelity requirements for a frontal impact dummy face, defined in terms of four tests; each impacting a different portion of the face with a pendulum impactor and defining the required response in terms of pendulum force versus time or resultant head CG acceleration. The upper limits for each test are shown in Table 4.1.3.

Test	Requirement
Face Test 1 Upper Bound Impact Force to Nose	3.69 kN
Face Test 2 Upper Bound Impact Force to Maxilla	8.2 kN
Face Test 3 Upper Bound Head Acceleration (from Frontal Bone Impact)	2500 $m.s^{-2}$
Face Test 4 Upper Bound Head Acceleration (from Zygoma Impact)	780 $m.s^{-2}$

Table 4.1.3: Upper Load and Acceleration Requirements for a Face Form or Dummy Face – FID Project Biofidelity Requirements

Face Test 1 - based on the experimental procedures used by Nyquist (1986). The test uses a horizontal guided impactor, mass 32 kg, diameter 25 mm, impact velocity 3.6 $m.s^{-1}$.

Face Test 2 - based on Melvin and Shee (1988). This is a full face test using a flat disk horizontal guided impactor, mass 13 kg, diameter 152 mm, velocity 6.7 $m.s^{-1}$.

Face Test 3 - based on ADRIA (1998). The tests is a 3.84 $m.s^{-1}$ 30° angled horizontal impact test to the frontal bone using a rigid impactor, mass 17 kg, diameter 25 mm.

Face Test 4 - identical to Face Test 3 except the impact is to the zygoma instead of the frontal bone.

These tests give an indication of the maximum force any new facial injury detection device may need to withstand.

For this application a minimum force detection of 10 kN is required with an ability to withstand loading at a minimum of 15 kN.

4.1.1.1 Other Facial Injuries

Facial injuries such as lacerations and burns can be more serious in terms of their long-term effects than factures. These types of injuries may also be sustained in bus or rail crashes, but are harder to characterise as injury criteria for these injuries do not exist and would be difficult to develop.

4.1.2 *Earlier Facial Injury Assessment systems*

A number of frangible faceforms were developed during the 1970s and 1980s for the purpose of detecting facial injuries due to steering wheel contact in a frontal crash. It is not the intention of this project to further such developments at present.

The EC ADRIA Project (PL96-1074) summarised the most recent face form technologies available:

The THOR face consisted of five load plates with load cells behind them, covered with confor foam. The main problem with this design was the tendency for inaccurate results if the load plates were impacted towards the edge of the load plates.

The Volvo DLSF consisted of six load cells with deformable inserts.

Other historic designs were considered, mainly involving deformable elements. Frangible face plates were used in some designs where failure indicated injury but did not measure the applied force or pressure in any way. This review included the TRL aluminium honeycomb design which was designed to crush at the same pressure as would cause fracture of the zygoma – apart from the obvious calibration problems with this design, it was a flat form, not representative of the normal shape of a face.

The main conclusions of the review may be summarised as follows:

- **Load Measuring Capability of Dummy Faces**
  - The GM face was unable to detect the risk of facial injury, as it had no instrumentation to measure the force of impact directly.
  - Impact tests and quasi-static tests have shown that the load cells in the Volvo Deformable Load Sensing face were significantly under reading the applied load. This is caused by the type of load cell, which is sensitive to the mounting technique used. The design of the Volvo DLSF needs modification before a reliable assessment can be made of the capabilities of this device in terms of facial injury risk.
  - The force measurement from the THOR face load cells was not repeatable and the output was very sensitive to the point of application of force to each load cell. The forces measured on the load cell were not accurate. These results caused further concern over the THOR face load cell measurement capability and the confidence in the results obtained. The performance of the current design of the THOR face was not acceptable; however, even with the problems it appeared to be able to distinguish between the performance of steering wheels in a consistent manner. The design of the THOR face could be improved by wiring together several load cells under the corners of each loading plate or by using larger load cells. The added complexity and the mass distribution of the head would need to be considered in each case.
- **Biofidelity of Dummy Faces**
  - The GM face showed good biofidelity for the rigid bar impacts to the zygoma and forehead regions, at impact velocities where a fracture occurred in the PMHS tests. The padded disc resulted in biofidelic attenuation of the impact, but the rigid impactor did not. The maxilla showed good biofidelity for an impact velocity of 1.5 to 3 $m.s^{-1}$ with respect to the peak contact force amplitude, but showed a less steep slope and wider pulse. The forehead only showed a biofidelic response at 4.3 $m.s^{-1}$ for all three parameters. The zygoma had a poor biofidelity.
  - The Volvo face tended to exhibit a response closer to that of a non-fractured face as opposed to a fractured face.
  - The biofidelity of the response of the THOR face to impact was not assessed as part of the ADRIA project and so no conclusions can be drawn.

- **Design Recommendations for Dummy Faces**
  - For a frontal impact test dummy, the face should have a smooth profile for repeatability.
  - The face should have the appropriate dynamic response to impact from distributed and concentrated forces for an uninjured face.
  - The load cells must be robust and insensitive to location of the applied force on the loading plate and should be capable of measuring at least the axial force.
  - The ability to measure shear forces may also be beneficial in order to obtain the true impact vector. For example, high vertical shear forces measured at the mid-face region could indicate a risk of penetration of eye sockets or nose, resulting in fracture.

4.2 Other Injury Tolerance Data

In addition to facial injuries, which are the main focus of this study, this report also contains some information on knee and abdomen injuries and the results presented below.

4.2.1 Knee Injuries

Fracture tolerance data have been generated by a variety of research institutes based on two different fracture mechanisms: knee pocketing (where the knee joint is loaded via the tibia due to the floor being pushed upwards and inwards by the crash and the knee being constrained by the dashboard); and direct knee loading through the dashboard, along the axis of the femur.

Banglmaier *et al*. (1999) loaded PMHS knee joints through the tibial axis with the joint at 90° and obtained a fracture tolerance of approximately 8 kN. However, this study also indicated that energy (based on kinetic energy of impactor) was a better predictor of injury.

Roberts *et al*. (1987) performed knee impacts to the knee along the femoral axis which indicated a fracture tolerance for the patella in the region of 9 kN. Melvin *et al.* (1975) and Viano *et al*. (1978) performed similar impacts to obtain fracture tolerances of the order of 7 kN.

For this application a minimum force detection of 6-7 kN is required with an ability to withstand loading at a minimum of 12 kN.

4.2.2 Abdominal Injuries

The FID project conducted a brief literature review of previous injury criteria research in this area. Impact force was found to be a poor injury predictor and hence injury criteria are usually in the form of the viscous criterion (V*C - a combination of compression and the velocity of compression, Lau and Viano, 1986) or compression data. The FID project proposed a combination of the specific V*C levels listed below together with belt loading compression of less than 48%.

Location	**V*C for AIS3 ($m.s^{-1}$)**
Upper	3.02
Middle	3.83
Lower	8.03
Right	3.53
Left	4.69

Table 4.2.1: Injury Criteria Tolerance Levels for various Abdominal Regions

Since abdominal injury criteria are based on abdominal compression, it is especially important that any device designed to detect abdominal injury be as biofidelic as possible with respect to force-compression response.

4.3 Applicable Standards

4.3.1 Pedestrian Head Impact Applications

Existing standards relate to brain injuries, not to facial fractures.

4.3.2 Headform Standards

A number of different test procedures exist in which the head of a human is replicated by some form of surrogate in a procedure to evaluate the risk of head injury. The most serious injuries are brain related thus the assessments are all based on brain injury as measured by the parameter of HIC (Head Injury Criteria), or HPC (Head Protection Criteria). These parameters are derived in exactly the same way.

The key Regulations in which headforms are used to assess structures and surfaces are Regulation 21 (Interior fittings), Regulation 17 (Seat back strength) and Regulation 43 (Windscreens). All of them use rigid impactors focussed on the assessment of brain injury. Some of the regulations refer to post-impact sharp edges, but the assessment of what a sharp edge is, is very subjective. Chamois leather over the surface of a headform has been used to measure the risk of cuts, but it has never been used within a Regulation.

None of the existing headform standards or test procedures assesses facial fracture injury risk.

A new European Directive (2003/102/EC 2006) has recently become operable in which ‘rigid’ headforms, covered in a vinyl type skin are used. In the US a free flight headform is used based on the Hybrid III dummy head. Again this is a rigid headform covered in a vinyl skin material.

5 Requirements for a Facial and Other Injury Detection Device

5.1 Introduction

When defining the specification for an anthropometric test device (ATD) a number of issues must be considered:

- Injury tolerance loads (i.e. the load that must be detected);
- Maximum load the device must survive (capable of withstanding a minimum of 20% above maximum injury tolerance, for example);
- Direction of load applied to the device. For example, in addition to direct loading there could be:
    - Shear
    - Bending
    - Oblique loads
- Sensitivity – e.g. suitable resolution for a device intended to give a visual display such as pressure sensitive film.
- Sampling (20 kHz for forces, accelerations, etc)
- Rates of loading
- Repeatable response (Coefficient of Variation = ±7% for selected measurement parameters)
- Reproducible response (Coefficient of Variation = ±10% for selected measurement parameters)

For most of these requirements there is only minimal information available. Some will also need further definition during the second phase of the project.

5.2 Expected Load Range

The expected loads that the instrumentation is likely to be subjected to during testing is indicated in Table 6.2.1 below:

Body Region	Expected (kN)	Overload allowance (kN)
Face	10	15
Knee	6-7	12

Table 6.2.1 - Expected Design Loads by Body Region

5.3 Direction of Load Applied

Little information is available considering loading patterns other than direct loading, either to the face or to any other body region. This aspect of the design is more likely to be a consideration for the face and abdomen rather than for the knee, which is likely to be loaded in either the anterior-posterior direction (due to intrusion) or laterally.

5.4 Rates of Loading

No information was found regarding the rates of loading to the face in the accident scenarios postulated in Section 3.

5.5 Robustness Issues

The required robustness of any final design will depend to some extent on whether it is to be implemented as part of a sub-systems test or as part of a full-body ATD to be used in crash tests. Current full-body ATDs often have robustness defined in terms of multiples of the injury threshold load applied. It should be noted that any requirement for robustness applies to the instrumentation as well as the physical structure of the device.

5.6 Sensitivity

The device must be sufficiently sensitive to differentiate between injurious and non-injurious loading. One problem with the injury tolerance levels given in the literature (see Section 4.2) is that they are in terms of force applied and many of the measurement technologies being considered measure pressure. Hence the following information has been included to be used in conjunction with Table 4.1.1 for the assessment of possible measurement technologies.

Details of impactors used to generate existing fracture tolerance data:

Nahum (1968) – Contact tip area of 1 square inch (645 mm^2), covered with a crushable nickel pad, 0.2 inches (5mm) thick of varying densities (9, 7 and 3% by weight); impact velocity and mass of impactor are not specified.

Hodgson *et al*. (1970) – Two different impactor forms were used; one with radius 1 inch (25.4 mm) the other 5/16 inch (7.9 mm), both 6.5 inches (165 mm) long and applied with longitudinal axis parallel to the sagital plane. The impactor mass was 10 lb and each impactor was dropped from heights of 5 inches (127 mm) and above.

Schneider *et al.* (1972) – Same experimental technique as employed by Nahum (1968), but extending the work to include the mandible and maxilla.

Nyquist *et al.* (1986) – 32 kg or 64 kg impactor, aluminium bar with diameter 25 mm, aligned with longitudinal axis parallel to left-right axis of the head; anterior to posterior path, impact velocities from 10 to 26 km/h (2.8 to 7.2 $m.s^{-1}$). Nyquist has generated force-penetration curves for the face from this data – may be usable for biomechanical response and or injury criteria. Authors concluded that impactor kinetic energy was related to fracture severity but that penetration was not.

Welbourne (1989) – Used the same impactor design as Nyquist but with mass 17 kg, impact velocity range 1-4 $m.s^{-1}$.

ADRIA – cylindrical bar impactor simulating a steering wheel rim – size not specified.

5.7 Repeatability and Reproducibility

These are usually defined in terms of the coefficient of variation (CV) a repeatability of response with CV_{max} ±7% is considered good and reproducibility of CV_{max} ±10%.

6 New and Emerging Technologies Considered

This section summarises the technologies available for use in investigating the forces exerted on parts of the body during a crash, principally the face, although the possibility of applying these technologies to other regions can be considered.

Body regions may be classified as being mostly hard (bony) tissue or mostly soft (fleshy) tissue. For example, the face and knee are hard tissue areas, while the abdomen is a soft tissue area. Some sensors may be better suited to measurements for hard tissue, which are required to withstand comparatively high forces up to levels capable of breaking bones. Soft tissues behave differently, and do not afford as much protection to underlying organs, such as, in the abdomen, the stomach or liver.

The available technologies can be broadly classified as being distributed sensors or discrete sensors. They can be further classified as being contact or non-contact (principally light-based).

This section describes a number of possible technologies. Table 6.1.1 below summaries the details of the recommended systems for the readers convenience. Properties and additional information of other systems are summarised in a table in Appendix A.

6.1 Summary of Recommended Systems

System		Application	Type of data produced	Example Costs
Advanced systems	Fibre optic distributed sensing 7.2.1.	Soft and hard tissue	Separate data points	Sensors £400 each Drive electronics £26,000 Special-purpose software £10,000 System available for rental at £3,000 per month for initial trials
	Sensor skins 7.2.3.	Soft tissue	Force distribution map	Skins £1,000 to £5,000 Drive electronics and software £5,000 to £25,000
	Fibre optic discrete sensors 7.3.1.	Soft and hard tissue	Separate data points	Sensors £300 each Drive electronics £2,000 to £20,000 Special-purpose software £10,000
	Pressure maps 7.3.3.	Hard tissue	Force distribution map	Maps £500-00 to £3,000 Drive electronics and software £5,000 to £25,000
Simple systems	'Carbon paper' 7.2.5.	Soft and hard tissue	Force distribution map	£100 - £1,000 per m^2 Scanning equipment £10,000
	Load cells 7.3.2.	Hard tissue	Small number of datum points	£400 per load cell Use TRL DAUs

Table 6.1.1 Summary table: Technologies suitable for tissue injury risk investigations

6.2 Distributed Sensors

Distributed sensor systems consist of a group of sensors arranged to cover a space (linear or area). The outputs from the group can be used to generate a 'map' of the physical quantity being measured.

6.2.1 Fibre Optic: Distributed Sensing

6.2.1.1 Technology

Optical fibres transmit light (visible or infrared) along a transparent cylindrical medium (the 'core') which is sheathed with a protective transparent covering (the 'cladding') which has a lower refractive index. Total internal reflection takes place at the core / cladding interface, allowing the light to be transmitted for considerable distances. Careful design of the refractive index profile within the core ('graded index') can prevent different path lengths from distorting the shape of light pulses by allowing light in the outer parts of the core to move more quickly through regions of lower refractive index than through regions of higher refractive index near the centre of the core. A similar effect can be obtained by using a linear refractive index profile with a narrow core, so that the light takes only a single or very small number of paths ('monomode').

(Note: When light moves through a transparent physical substance such as glass its speed is considerably slower than the free-space velocity of light considered in relativity theory. The drop in light speed is given by the reciprocal of the refractive index of the physical substance.)

Optical fibre is not affected by electromagnetic fields and is therefore immune to electromagnetic interference (EMI), but it does respond to other physical phenomena, notably temperature, pressure, and changes of shape. This can be utilised to construct highly robust sensors for these physical quantities.

One operating principle uses optical time domain reflectometry (OTDR). A pulse of light is transmitted into the fibre, and reflections occur along the fibre length due to mechanical changes such as bending or deformation due to pressure. These reflections are detected, and their amplitudes give a measure of the amount of deforming force, while the time taken for the reflection to occur (of the order of 5 ns/m) gives the location of the deformation.

Another method etches Bragg interferometry gratings into the fibre and measures the changes in interference fringes in the reflected light. The Bragg gratings can also be designed to reflect light of a specific wavelength. They are then illuminated by comparatively broad-spectrum (white) light, or by a tuneable laser, and the monitoring equipment checks the wavelength of the reflected light to measure the compression or stretching of the Bragg element, which is an indication of strain in the fibre.

An example of a fibre optic sensing system can be found at:

http://www.smartfibres.com/index.htm

6.2.1.2 Potential Applications

The ability to read several sensors on a single connection is helpful in designing an impact-measuring body part form such as a face, since it reduces the number of physical connections required.

6.2.1.3 Typical Applications

Distributed fibre optic sensors are generally used in situations where:

- The location to be monitored is remote
- The location is hazardous

- A large number of sensors are required but there are limitations on the number of physical connections
- Any combination of these

A number of companies market such sensors, principally for use in extremely hostile environment. Typical applications would include:

Oil and Gas: A range of fibre optic strain and temperature sensing cable that can be incorporated into the construction of flexible risers and umbilicals used in permanent and temporary wellbore applications.

Process: Steel or speciality alloy-based cable used for a wide variety of industrial process applications (including process optimisation and control, refinery, gasification, leak sensing).

Power: Suitable for monitoring power cables for dynamic cable rating, fire detection and tunnel ventilation. Can often be installed on the exterior of the power cable.

Dam: Used for detection of movement or seepage, and for monitoring pressure in standpipes

Fire sensing: Steel tube-based cable suitable for use in harsh environments (e.g. tunnels, conveyor belts, car parks).

Automotive manufacture: For the production car industry, much development activity is carried out using new materials and alternative designs to get the best performance to weight ratio of structural components. Distributed optical fibre sensors can be used for design validation of scale models and prototype components on test rigs and within wind tunnels during a vehicle's development cycle.

6.2.1.4 Strengths

The sensing element (the optical fibre) is simple and comparatively cheap to manufacture, very durable, and easily replaceable.

The fibre sensors are completely immune to EMI, RFI, and lightning.

Large distances (km) and areas can be covered by the fibres.

The sensing element can be designed to have specific resolution determined by the spacing of the Bragg gratings.

6.2.1.5 Weaknesses

The measuring electronics, for example the time domain reflectometer, is comparatively expensive.

The sensor elements are temperature sensitive, and for applications where measurements are made over long timescales (typically hours or more), temperature compensation would be required. Short timescale measurements over minutes or less, such as are encountered in impact testing, would not require temperature compensation, provided the sensors are used at or close to their calibrated temperature range.

6.2.1.6 Typical Costs

Costs of these systems vary considerably. A local company markets systems for a number of applications at prices from £6,000 to £60,000. This company has supplied a specimen quote for an off-the-shelf system which would be close to meeting the needs of the project of £400 per sensor fibre (25 required) and £26,000 for the drive electronics. Additional software may need to be purchased or produced in-house at an estimated cost of £10,000. This gives a total budget price of £46,000.

The local manufacturer is willing to make a system available for rental at £3,000 per month, for an initial trial.

6.2.2 *Laser Doppler Velocimetry*

6.2.2.1 Technology

Laser doppler scanners use a Fabry-Perot interferometer, which analyses the doppler shift of light reflected from a moving object. This is displayed as a dynamic fringe pattern using an electro-optic streak camera. The velocity of the illuminated object causes a shift in frequency of the light. This measured velocity can be anywhere in the range of 350 $km.h^{-1}$ to 11,000 $km.h^{-1}$. If the mass of the moving object is known, its acceleration gives a measure of the force acting on it. The technique is non-contact and therefore useful in extremely hostile environments. It is also capable of very high resolution.

An example of a laser doppler sensing system can be found at:

http://www.awe.co.uk/main_site/scientific_and_technical/featured_areas/hydrodynamics_contents/esr-contents/esr-c/esr-c2/index.html

6.2.2.2 Potential Applications

These systems would be unsuitable for use in human injury analysis, since the speed levels of the objects which they are designed to monitor would be too high for the situations likely to be encountered and survivable by humans.

6.2.2.3 Typical Applications

Laser doppler velocimetry would be used in situations where:

- It is necessary or desirable to have no physical contact with the object or objects being monitored
- The situation is very hazardous

These systems are used in applications such as blast monitoring in explosions.

6.2.2.4 Strengths

The sensors are highly robust, being non-contact.

6.2.2.5 Weaknesses

The system electronics are expensive.

Velocity range too high.

6.2.2.6 Typical Costs

Costs are likely to be very high, of the order of £100,000 per system.

6.2.3 Sensor Skins (Robotics)

6.2.3.1 Technology

Sensor skins are flexible membranes with tactile sensing elements (taxels or sensels) integrated into their structure and addressed as a matrix in an x-y format. Such membranes can in principle be made very large, with the limiting factors being the number of read-out connections required, the time taken to perform the readout, and the response time of the sensors.

The sensor elements may be capacitive or resistive, and their electrical properties vary with pressure. They may also incorporate MEMS (Micro-Electro-Mechanical Systems**)** devices.

As an example, 'Tactilus' is an electronic sensor system which can measure contact pressures from as low as 0.007 to 14.10 kg/cm2 (0.01 to 200psi). At the heart of the system is a thin flexible sensor skin that is densely packed with thousands of sensing points. These sensing points can be as close as 1 mm (0.04 inches) apart and can collect data as rapidly as 65,000 points per second. The sensor skin has a minimum thickness of 0.8 mm (0.03 inches), allowing adaptation over curved surfaces or in invasive intolerant environments.

An example of a sensor skin sensing system can be found at:

http://www.sensorprod.com/tactilus.php

6.2.3.2 Potential Applications

In human injury analysis, they would be suitable for soft tissue simulation, due to their flexibility and sensitivity.

6.2.3.3 Typical Applications

Generally 'sensor skins' can be used in any situation where accurate and sensitive two-dimensional data is required. Tactilus has been used in measuring the precise pressure distribution within a laminating press for multilayer pcbs, and in analysing the contact between a heat sink and heat source, such as a transistor.

Sensor 'skins' are often designed to mimic the human sense of touch and are suitable for use in robotics.

6.2.3.4 Strengths

They are very sensitive, specialising in measuring very low force levels. They are very flexible, allowing them to conform to complex surfaces.

6.2.3.5 Weaknesses

Sensor skins are likely to be limited in the range of forces they can measure, and to be somewhat fragile.

6.2.3.6 Typical Costs

The costs of the 'skins' themselves will be of the order of £1,000 to £5,000, depending on size and resolution. The drive electronics and software will cost from £5,000 to £25,000 (dependant on speed and number of channels).

6.2.4 *Force Distribution (Pressure) Mapping*

6.2.4.1 Technology

Force distribution systems, more commonly known as pressure mapping systems, are similar to sensor skins, but generally offer higher force measurement ranges. They tend to have somewhat lower resolutions but are still generally capable of resolution of the order of 1-2 mm.

A typical pressure measurement system such as Tekscan comprises an extremely thin (0.1 mm), flexible tactile sensor. Sensors can come in both grid-based and single load cell configurations, and are available in a wide range of shapes, sizes and spatial resolutions. Tekscan sensors are capable of measuring pressures ranging from 0-15 kPa to 0-175 MPa.

The standard sensor consists of two thin, flexible polyester sheets which have electrically conductive electrodes deposited in varying patterns. In a typical system, the inside surface of one sheet forms a row pattern while the inner surface of the other employs a column pattern. The spacing between the rows and columns varies according to sensor application and can be as small as ~0.5 mm.

Before assembly, a thin semi-conductive coating (ink) is applied as an intermediate layer between the electrical contacts (rows and columns). This ink provides the electrical resistance change at each of the intersecting points.

When the two polyester sheets are placed on top of each other, a grid pattern is formed, creating a sensing location at each intersection. By measuring the changes in current flow at each intersection point, the applied force distribution pattern can be measured and displayed on a computer screen. Software can be provided to make force measurements either statically or dynamically and the information can be seen as graphical 2-D or 3-D displays.

In use, the sensor is installed between two mating surfaces. Tekscan's matrix-based systems provide an array of force sensitive cells that enable measurement of the pressure distribution between the two surfaces.

The 2-D and 3-D displays show the location and magnitude of the forces exerted on the surface of the sensor at each sensing location. Force and pressure changes can be observed, measured, recorded, and analyzed.

Sensels within a matrix can be as small as 0.140 mm^2, so that a one square centimetre area can contain an array of 170 of these locations. Sensor matrices have been made covering 1,600 square centimetres, with over 100,000 sensing locations.

Discrete or semi-discrete versions (with a small number of sensels or single sensels) can be made for certain applications.

An example of a pressure mapping sensing system can be found at:

http://www.tekscan.com/industrial/tirescan_system.html

6.2.4.2 Potential Applications

For human injury analysis, they would be able to handle force levels of the magnitude required to fracture bones, and so would be suitable for hard tissue work.

6.2.4.3 Typical Applications

Typical applications include situations where moderately high levels of force are required to be measured over fairly small areas, perhaps less than a square metre.

Examples of industrial applications include tyre tread force distribution mapping, medical uses such as the measurement of pressures experienced from the mattress by bed-bound patients, and sports uses such as the measurement of pressures experienced by the foot from the soles of sports footwear.

6.2.4.4 Strengths

Pressure maps tend to be more durable than sensor skins. They are moderately flexible, allowing them to conform to shaped surfaces.

6.2.4.5 Weaknesses

Pressure maps tend to be less flexible than sensor skins.

Previous experience of this technology, as provided by Tekscan, has shown that the material requires recalibration between uses.

6.2.4.6 Typical Costs

The costs of the ‘maps’ themselves will be of the order of £500 to £3,000, depending on size and resolution. The drive electronics and software will cost from £5,000 to £25,000 (dependant on speed and number of channels).

6.2.5 'Carbon Paper'

6.2.5.1 Technology

This is a group of single-use sensor films that contain a layer of micro-encapsulated pigment and a layer of ‘developer’. Pressure causes a number of the microcapsules to burst and release pigment into the developer, causing a visible colour change whose density is dependent on the force used. Higher pressures burst more capsules and give greater pigment density. The resulting image can be estimated by eye against a colour chart or scanned optically and evaluated by software.

An example of a ‘carbon paper’ system can be found at:

http://www.sasusa.com/html/pressurex_film.html

6.2.5.2 Potential Applications

They would be suitable for both soft and hard tissue analysis, and can be formed into complex shapes to cover head - and knee-forms.

6.2.5.3 Typical Applications

‘Carbon papers’ are very thin (Pressurex: 100 to 200 microns) - enabling them to conform to curved surfaces, and are ideal for invasive intolerant environments and tight spaces, where a visually detailed analysis of stress between two surfaces is needed.

Applications include metal and ultrasonic welding, roller nips, clutch and brake plates, materials lamination, electronic component packaging, heat sinks and seals, impact forces, plastics processing, particulates and sprays.

6.2.5.4 Strengths

These are disposable systems which offer possibly the lowest cost pressure-mapping system. They can be designed to handle a very wide range of operating pressures (Pressurex: 2 - 18,500 psi in six ranges)

6.2.5.5 Weaknesses

The mode of operation of these systems does not permit dynamic applications, that is, it is not possible to monitor changes in force levels.

6.2.5.6 Typical Costs

Sheets of ‘carbon paper’ such as ‘Pressurex’ cost about £100 to £1,000 depending on size. Scanning equipment is available to measure the colour change and produce a pressure map, and this equipment costs of the order of £10,000 per system.

6.3 Discrete Sensors

Discrete sensors are single sensors which measure a physical quantity at a single point. Devices can be used in groups to cover the area of interest, but unlike distributed sensors, each device has a dedicated connection.

6.3.1 Fibre Optic: Discrete Sensors

6.3.1.1 Technology

A discrete optical fibre sensor consists of a resonant optical cavity with a deflectable diaphragm at one end. At the other end light is introduced into the cavity. As pressure on the diaphragm varies, the length of the cavity changes, altering the reflection characteristics in a measurable way.

An example of a discrete fibre optic sensing system can be found at:

http://www.sequoia.co.uk/sensors/Manufacturers/FISO/fibreoptic_sensor_pressure.php

6.3.1.2 Potential Applications

For human injury measurement, they can be integrated into shaped impactors such as headforms.

6.3.1.3 Typical Applications

These devices measure moderate to high pressures, typically up to 1000 PSI, and are suited to use in harsh, hazardous or high temperature operating environments such as those found in oil & gas, aerospace and industrial applications.

They are also used in minimally invasive medical applications such as internal measurements of arterial and venous blood pressure.

These sensors can be used to fabricate medium to high resolution pressure mapping arrays.

6.3.1.4 *Strengths*

Such a device can be very sensitive to small pressure changes and can be made very small physically. Medium to high resolutions are possible.

The sensor heads are comparatively cheap to manufacture and easily replaceable.

Like all fibre optic systems they are completely immune to EMI, RFI, and lightning.

6.3.1.5 *Weaknesses*

The light source and measurement electronics is comparatively expensive but likely to be cheaper than the OTDR systems described earlier.

6.3.1.6 *Typical Costs*

Individual fibre sensors cost around £300. The drive electronics costs from £2,000 to £20,000 (dependant on speed and complexity). Additional software may need to be purchased or produced in-house at an estimated cost of £10,000.

6.3.2 *Load Cells*

6.3.2.1 *Technology*

A widespread technology used to measure forces is the load cell.

Early designs used a strain gauge to measure the direct stress which is introduced into a metal element when it is subjected to a tensile or compressive force. A bending beam type design uses strain gauges to monitor the stress in the sensing element when subjected to a bending force. The strain gauges are bonded on the flat upper and lower sections of the load cell at points of maximum strain. This load cell type is used for low capacities and performs with good linearity. Its disadvantage is that it must be loaded correctly to obtain consistent results.

More recently the measurement of shear stress has been adopted as a more efficient method of load determination as it is less dependent on the way and direction in which the force is applied to the load cell. The strain gauges are bonded to a reduced part of the cross section of the beam in order to maximise the shear effect. They are bonded at 45 degree angles on either side of the beam to measure the shear strains.

An example of a load cell sensing system can be found at:

http://www.sensotec.com/loadcell.asp

6.3.2.2 *Potential Applications*

Load cells have been used previously in facial impact tests, including systems mentioned in Section 5.

6.3.2.3 *Typical Applications*

The devices are capable of measuring high levels of force, in indoor or outdoor applications, or where the installation is subject to vibration, high winds or harsh environments,

Load cells find application in a number of areas:

- Vehicle impact testing, particularly the European New Car Assessment Programme (NCAP) crash tests, and incompatibility testing using load cell barrier walls and Mobile Deformable Barriers (MDB) with load cell faces.
- Loading assemblies for tank, silo and vessel weighing.

6.3.2.4 Strengths

The devices are very robust, and are tolerant of severe environmental conditions.

6.3.2.5 Weaknesses

The physical size restricts the resolution that can be achieved. In addition, it can be difficult to ensure that the force is applied to the sensor in the correct orientation.

6.3.2.6 Typical Costs

Honeywell Sensotec markets a range of subminiature load cells at around £300 - £400 a unit. The cost excludes a data acquisition system as it may be possible to use TRL's standard Data Acquisition Units (DAU).

6.3.3 Discrete Pressure Map Segments

6.3.3.1 Technology

Another kind of discrete sensor is derived from the sensor skins and pressure mapping devices described earlier. The construction is similar, but only a small number of sensels are used, covering a small area. Some types use a single sensel only.

An example of a sensing system by Digitacts can be found at:

http://www.pressureprofile.com/DigiTacts.php

DigiTacts are high-sensitivity capacitive single-point tactile sensors with a digital output and an I2C interface.

An example of a free form sensing system by Tactilus can be found at:

http://www.sensorprod.com/tactilus.php

Tactilus free form sensors are resistive discrete, single point sensors. Because of its use of resistive technology the sensor requires no additional interface electronics. Sensors are available off the shelf in a number of sizes and different pressure ranges.

6.3.3.2 Potential Applications

These devices would be suitable for use in facial injury risk testing needing a comparatively low resolution.

6.3.3.3 Typical Applications

These may be viewed as low-cost, low-force level equivalents of load cells. They would find application where only a small number of datum points are required.

6.3.3.4 *Strengths*

These devices are comparatively inexpensive compared to full-size pressure mats. They are lightweight and low-profile. In the case of Tactilus the sensors can be custom made for differing sensing areas/pressure ranges and can be connected directly to standard data acquisition equipment.

6.3.3.5 *Weaknesses*

Some variants are only suited to slow, low pressure applications.

6.3.3.6 *Typical Costs*

Costs of individual Digitacts are around £400 per unit. The drive electronics and software are around £5,000 to £20,000 (dependant on size of skin and number of sensing elements).

6.4 Improvement to "Low Test Cost" Impactor Systems

TRL Engineering Services held a brainstorming session to propose improvements to existing "low test cost" impactor systems that are known to be problematic in application. The results are as below.

The Problem

The perceived complications with aluminium honeycomb impactor characteristics requiring improvement by a replacement impactor include:

- Edge effects
- Cells are not independent
- Difficult to measure crush

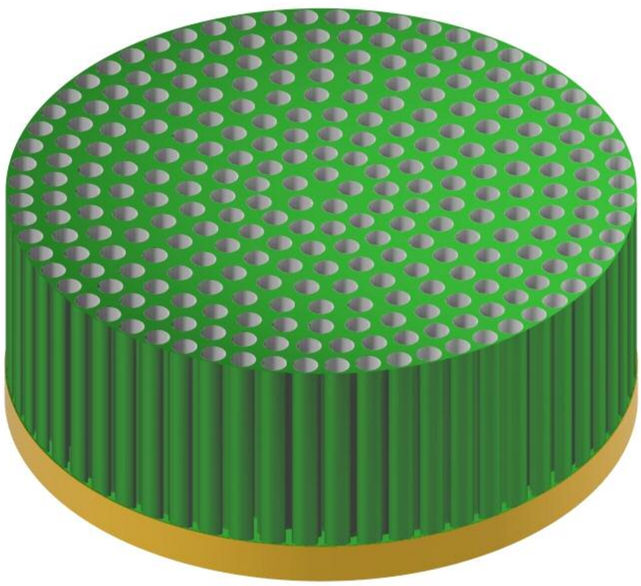
6.4.1 Concepts Considered to be Potentially Useful but Finally Rejected on Costs

6.4.1.1 Crush Tubes in Support Medium

- Thin walled individual crush tubes in a supporting medium

The basis to this concept combines the repeatability of crush tube technology with functionality and resolution of honey comb. The crush tubes would be supported in a deformable medium such that the direction of crush is parallel to the impacting device whilst negating the edge effects associated with the glued layers of honeycomb. The easily deformed support medium would also provide a smoother impression of the impacted object helping to improve the accuracy of the measured crush depth.

6.4.1.2 Outline Design of a "LowTest Cost" Facial Impactor



TRL generated CAD image

The design concept for the "low test cost" facial impactor built upon previous knowledge and experience gained through the use of aluminium honeycomb for the same application. Aluminium honeycomb is known to have a problem with localised edge effects and these were encountered during earlier facial impactor work. As such, any new device must be designed to overcome this problem whilst still maintaining a comparable impactor resolution to the ¼ inch honeycomb used in earlier test studies.

The schematic shown above is a graphical representation of the proposed solution. The device comprises of a mounting plate, approximately 300 crush tubes and a tube supporting medium in the form of oasis type foam. The concept is built upon the linear response and repeatability of crush tube technology whilst still maintaining a comparable resolution to honeycomb. However, in this guise the localised edge effects of the glued honeycomb have been negated. The crush tubes proposed are 50 mm long, 5251 aluminium tubes of 6 mm diameter with a wall thickness of 0.05 mm (again closely matching the physical geometry of the honeycomb). The inclusion of the support medium serves two purposes; primarily used as a support device to ensure that the tubes crush in a controlled manner, but also to improve the definition of the imprint left by test subject post event for measuring. Of course, the crush characteristics of the medium would have to be considered but, it was felt that this would not have a significant effect on the performance of the device.

6.4.1.3 Discussion of Test Costs for Proposed "Low Test Cost" Impactor

When further research was completed with a view to establishing costs for manufacture a problem was encountered. The diameter and wall thicknesses of the tube required for the device would involve highly specialised bespoke manufacture with costs in the region of £60+ per metre. The bespoke nature of the product is due to the specialised size requirements, a very small market demand and a lack of suitable stock items. This is also compounded by the fragility of the component and the associated difficulties in safe and economic storage. This would mean that for each individual device the tube costs alone would be ~£900. The cost of the reusable backing plate and oasis become negligible in relation to the tube costs, however, at approaching £1,000 per "low cost" facial impactor test, the project and test procedure is considered unsustainable.

6.4.2 Other "Low Test Cost" Concepts Considered but Rejected

6.4.2.1 Viscous Medium

- Direct impact
- Indirect application – rods or pins to follow the contour of the impactor and react against the medium to record crush depth

The use of a viscous medium was ruled out as all solutions would be subject to rate effects and therefore not provide accurate and comparable data.

6.4.2.2 Spears and Olives

- Oversized sphere into aluminium tube

This idea was rejected on the basis of a lack of control. The tolerances of the parts required to achieve repeatability would significantly increase the cost of the unit beyond that which is reasonable for a "low cost" test. In addition it would be difficult to allow for the combined effect of the force required for deformation and the frictional force to be overcome upon impact.

6.4.2.3 *Electromagnetic*

- Electromagnetic Physical Resistance to Motion

This concept was thought to be impracticable due to the significant variance of force with distance.

6.4.2.4 *Mechanical Friction Devices*

- Clamped Element between surfaces with or without friction material

As with a number of the concepts generated, the control aspect is the most significant downfall of mechanical friction devices. The greatest area of concern lay in the transition from static to sliding frictional forces.

6.4.2.5 *Spring Force*

- Spring Retarded Rod into Impressionable Material

In order to achieve the required impactor resolution, a total of 351 springs would be required. This equates to a required force of 71 N per unit in a spring of diameter ~ 6 mm. Conceptually, if this were achievable, the indentation in the impressionable medium could then be measured to determine the crush on the device. However the spring force required renders this concept unrealistic.

7 Selection of Systems

The following is a summary of recommendations for the various sensor types. It should be noted that these recommendations may mention, but do not specify any particular manufacturer or sensor, and that any choice should take into account specific details such as speed of response, accuracy, and repeatability.

7.1 Technologies Suitable for Tissue Injury Risk Investigations

7.1.1 Simple Systems

- 'Carbon paper' would be suitable for both 'soft tissue' and 'hard tissue' applications, as a cheap, single-use technique where only peak force or pressure is required (i.e. not dynamic force-time or pressure-time information).
- Load cells can be used for 'hard tissue' applications where a small number of high-force datum points would be acceptable.

7.1.1.1 Costs of Simple Systems

- 'Carbon paper' is possibly the lowest cost option, of the order of a £100 - 1,000 per square metre. The bulk of the cost would be in using automated optical analysis software and hardware, expected to be around £10,000.
- Honeywell Sensotec markets a range of subminiature load cells at around £300 - 400 per unit.

7.1.2 Advanced Systems

- Sensor skins would be suitable for 'soft tissue' applications such as the abdomen.
- Pressure maps would be suitable for 'hard tissue' applications such as face and knee.
- Fibre optic discrete sensors could be used as an alternative to skins and maps, but would be mechanically awkward to mount in an impact test form.
- Fibre optic distributed sensing would be suitable for injury risk measurements provided the sensing element is designed with a suitable resolution. These have the advantages of placing a number of sensing elements on a single physical channel. The scanning equipment has the task of distinguishing between sensors on each physical channel.

7.1.2.1 Costs of Advanced Systems

- Sensor skins and pressure maps including scanning equipment are of the order of £5k to £25k, somewhat dependent on the size (and number of sensing elements) of the skin or map.
- Discrete sensors using pressure map technology such as Tactilus discrete units are quoted at around £30 per unit and may be connected directly to TRL data acquisition equipment. Custom designs of these discrete units would incur a tooling cost of about £2,500.
- Fibre optic discrete sensors have a budget cost of £300 each but require scanning equipment estimated to be up to £30,000 (including software).
- Fibre optic distributed sensing elements would cost approximately £400 per element (fibre) which would contain up to 30 separate sensors (Bragg gratings) per element.

Again the scanning equipment would cost approximately £36,000 (including software), depending on speed and complexity required.

7.2 "Low Test Cost" Impactor Systems

- It was initially suggested that an impactor based on thin walled individual crush tubes mounted in a supporting medium would be suitable.
- Although this looked promising technically it was later rejected on cost. The cost of the crush tubes required per test would be in the region of £1,000, for a 150 mm diameter impactor which was considered too much for a "low cost" test.
- This system would not provide as much data as the preferred fibre optic system option suggested in Section 8.

8 Conclusions

- We have identified a considerable amount of facial injury tolerance data, mostly generated with injuries due to steering wheel contact in mind, but which is applicable to other vehicle and non-vehicle facial injury prediction scenarios.

- A distributed sensor fibre optic system would be most suitable for further development within a second phase.

- A range of traffic and other activity areas has been identified that could potentially benefit from the use of the proposed fibre optic measuring system.

- It is considered that the distributed sensor fibre optic system recommended could be used on other non facial injury and soft tissue applications (the focus of this project).

- For facial applications a minimum force detection of 10 kN is required with an ability to withstand loading at a minimum of 15 kN.

- For the knee applications a minimum force detection of 6-7 kN is required with an ability to withstand loading at a minimum of 12 kN.

- A number of improvements to the 'low test cost' impactor system were considered. Only one development idea was thought worthwhile pursuing, which is based on thin walled individual crush tubes mounted in a supporting medium. However, on further analysis the likely costs of the consumables associated with such tests means that the objective of a "low cost" test is not likely to be achieved and therefore it is not recommended to develop this idea further, at this time.

9 Recommendations

The following recommendations are made for a possible second phase of research.

9.1 Fibre Optic System

- A proposal for a second phase of this project has already been submitted, which is designed to complete the development of a suitable fibre optic system. The fibre optic system could be based on an equipment supplier.
- The cost of the proposal is £103,000, which includes purchase of a 64 channel fibre optic system £36,000.
- The proposal would allow development of a fibre optic based system capable of measuring forces involved in impacts between body soft tissue areas and harmful objects.

9.2 "Low Test Cost" System

- Discontinue developing this system, due to unacceptably high test costs.
- Although a technical improvement was identified this idea was rejected on cost. The cost of providing crush tubes for an individual test, was considered to be too high to satisfy the objective of a "low cost" test.

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Appendix A. Summary Table: Sensor Characteristics

The sensor types are labelled as 'Green/ Amber / Red' to indicate order of preference:

Distributed sensor types

Sensor type (Section no)	Examples	Cost	Robustness	Resolution	Force range	Response speed	Comments
Fibre optic: (7.2.1.) Distributed sensing	Smart Fibres	Moderate to High	High	Various, typically 1cm - 10 m	Moderate to High	10 kHz sample rate is achievable	A number of sensors can be included on a single fibre
Laser Doppler (7.2.2.)	AWE	High	non-contact	<1mm	non-contact	monitor velocities in the range of 0.1 $km.s^{-1}$ to 3 $km.s^{-1}$	non-contact
Sensor skins (robotics) (7.2.3.)	Tactilus	Medium	Medium	0.05mm	0.001 - 2000 psi		
	Tactilus High Speed Impact Force Sensor				> 100 N/cm^2	20 kHz frequency response	Can be customised for shape
					or		
					> 145 psi		
Pressure mapping (7.2.4.)	Tekscan	Medium	Medium	25 - 1600 elements / in^2	6-25000 psi	100,000 sensors at 500 Hz	
						max. 44 sensors at 10 kHz	
	X3			0.5" - 1.25"	5-200 mm Hg	fewer sensing points at one time, with a maximum acquisition rate of 640,000	
				1.15mm - 5.08mm	2-200 psi		
'Carbon paper' (7.2..5.)	Pressurex	Low	Medium	5 - 15 microns	Various ranges, including:	N/A (peak values only after impact)	One-off use
					2-20 psi (0.14-1.4 kg/cm^2)		can be scanned visually or by
					28-85 psi (2-6 kg/cm^2)		
					70-350 psi (5-25 kg/cm^2)		

Discrete sensor types

Sensor type	Examples	Cost	Robustness	Resolution	Force range	Response speed	Comments
Fibre optic: (7.3.1.) Discrete sensors	Sequoia	Medium	Medium	0.1mm diam	-300 - +300 mmHg	200kHz sample rate	Attention needed to mounting method
				19mm diam	10 -10000 psi		Can be built into a face-form
Discrete force sensors (7.3.2.)	Digitacts	Low	Medium	10mm circle (typical)	0-20 psi	30Hz sample rate	
	Load cells	High	High	0.38” - 0.75 “	various ranges including 196.5 psi and larger	>20kHz	
	Sensotec Model 13			(9.6mm - 19mm)			