Design of Healthcare Facilities Utilising Established Injury Biomechanics Techniques for Injury Prevention

a report by

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The Design for Patient Safety Report of 2003[1] recommends a new approach to healthcare safety to reduce the potential for medical errors and accidents through the effective use of design in a whole-system context.

During the design of healthcare facilities, a key aim is to provide patients with the best possible outcome during treatment, and this includes reducing the risk of further injury. Arup is focused on the improvement of patient safety through holistic healthcare facility design.

The Design for Patient Safety Report 2003[1] concludes that the National Health Service (NHS) would gain greatly if it were to adopt modern thinking and practice with regard to designing for safety. This article aims to highlight methods applied to designing for safety in other industries that could assist in the design of healthcare facilities. These include:

- the use of computer human body models to optimise designs of stairways, ramps, etc. to reduce injury potential;
- the use of physical testing techniques to assess the critical fall heights (CFHs) of currently installed/proposed flooring in high fall-risk areas (e.g. around beds, baths, etc.); and
- a reduction in height of 'equipment' to match the CFHs of flooring surfaces or the installation of specially designed impact-absorbing materials to match the potential fall height for the equipment.

The author suggests that these state-of-the-art injury biomechanics techniques could assist in improving the design of healthcare facilities in the same way that computer modelling, physical crash tests and the installation of impact-absorbing interiors aim to reduce injury potential for road vehicle users.

Patient Falls

The National Patient Safety Agency (NPSA) estimates that in the UK over 530 patients every year fracture a hip by falling in hospital, and a further 440 patients sustain other fractures. Twenty-six falls that appear to have resulted in the death of the patient were reported to the NPSA between 2005 and 2006, and further deaths are likely to have occurred following hip fractures.[2]

Patient falls have both human and financial costs. The immediate annual healthcare cost of treating such falls is over £15 million for England and Wales. For individual patients, the consequences range from distress and a loss of confidence to injuries that can cause pain and suffering, loss of independence, an increased likelihood of discharge to residential or nursing home care and, occasionally, death.[2]

These statistics highlight the fact that patient falls are a serious problem, and current strategies to reduce falls tend to focus on management of patients and procedures for risk reduction. However, research has shown[3] that "as efforts to research the effectiveness of falls prevention strategies continue,[4] an additional area of research focuses on injury prevention strategies since the prevention of all falls is impossible".

Previous Injury Biomechanics Applications

Injury biomechanics research began in the 1930s, was carried out by the automotive and aerospace industries and has developed over subsequent decades utilising results from experimentation on animals, human cadavers, human volunteers and anthropomorphic crash test dummies. Advanced techniques now available include the use of detailed finite element (FE) models of crash test dummies and FE models of the whole human body and body segments (head, arm and hip).

Crash Test Dummies

Human physical test data on the mechanical response and injury tolerance of various body parts have been gathered from tests on cadavers, animal surrogates and volunteers, and these data aid in the assessment of the level of biofidelity (human-like mechanical response) of crash test dummies and the interpretation of test results to predict likely injuries.

Results from these physical tests have been applied to optimising the design of products specifically for protecting humans from injury, which include the assessment of less lethal weapons, protective body armour, protective padding for sports, playground surfaces and bicycle and motorcycle helmets. The mechanical response data have also been utilised for the generation and assessment of computer models of crash test dummies and humans.

Computer Modelling

Computer modelling techniques are continuously advancing and vehicle/aircraft structures are now commonly modelled using FE

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Figure 1: Finite Element Vehicle Interior and Crash Test Dummy

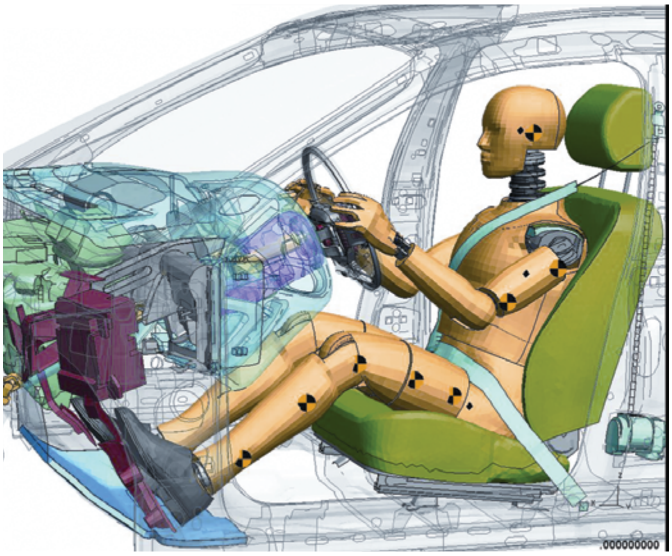
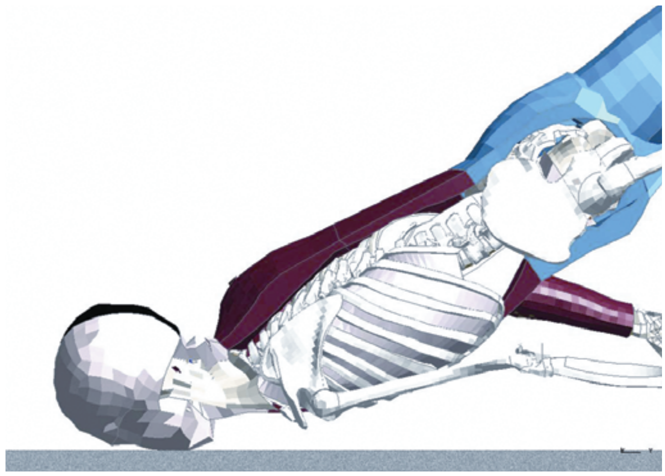


Figure 2: Total Human Model for Safety Finite Element Full Human Body Model Simulating Head Impact Due to a Fall



techniques. FE computer representations of crash test dummies are available to assess the prototype vehicle/aircraft FE models in terms of injury prevention before the physical prototype is tested (see *Figure 1*).

The computer models can be tested an infinite number of times while introducing minor perturbations and varying parameters relatively quickly and easily. This technique is used to optimise vehicle/aircraft crashworthiness, minimise occupant injuries and assess the design's adherence to the appropriate test standards. This design process aims to reduce the physical test programme and its associated costs.

As the crash test dummy computer models are direct representations of the physical crash test dummies, the limitations suffered by physical dummies are mirrored in the computer representation. The biofidelity of crash test dummies is suboptimal because there are many other design requirements to be considered, including design for manufacture (to simplify the manufacture of dummy parts), durability (to allow for multiple tests), reproducibility (to ensure all test centres are using similar crash test dummies), repeatability (to ensure simulations continue to provide reliable results after multiple impacts) and cost (to keep the product price competitive). These constraints limit the potential of computer models derived from crash test dummies for use where a high level of biofidelity is a primary requirement.

Since the 1990s, researchers have utilised data obtained directly from human volunteers and cadaver and animal studies to define the response of the human body under mechanical loading to design a variety of highly biofidelic computer-generated human body models.[5] This direct human replication removes the physical, regulatory and economic restrictions imposed on the previous computer simulations of 'physical' dummy models.

These human body models have been applied widely to reconstructing and analysing many types of injury scenario, including detailed whiplash, pilot ejection and windblast, gait analysis[6] and simulations of fall scenarios[7–9] (see *Figure 2*).

This technique can be applied to investigating falls that have already occurred or to analysing an environment in which a fall may occur in order to predict the likely injuries. As a fall is quite a simple event compared with a car crash, the human body models have proved effective in this area, and the time to model the environment and simulate the fall is relatively short compared with vehicle-impact simulations. *Figures 3* and *4* illustrate how these models can be utilised to assess two different designs in terms of injury potential.

In this example, the injury under assessment is head injury and a standard measure of head injury is the Head Injury Criterion (HIC).[10] *Figure 3* shows a fall down a standard straight staircase where the highest HIC recorded during the fall was 190 from the impact shown in sequence shot number nine at the base of the staircase. Modifying the design to include a quarter-landing halfway down the staircase reduced the stairway length and prevented further falling, and this reduced the highest HIC value to 72. This HIC was recorded from the impact occurring on the quarter-landing (see *Figure 4*, sequence number six).

Mathematics dynamics modelling (MADYMO) facet models (see *Figure 3* and *4*) are less complex than FE models (see *Figure 2*), and this reduced complexity results in reduced run times at the expense of detailed injury assessment. Full FE human body[11] and segment models (e.g. head, arm and leg) can provide more detail such as specific fracture types and locations. Researchers have developed detailed FE segment models to focus on injury analysis of specific locations of the body.[12–14] Another option is to utilise the FE segment models available in MADYMO[15] that can be attached to the less detailed facet full human body models so that the most computationally intense section of the model is focused on the injured area.

Investigating and Reducing Fall-related Injuries

Research reviewed by the author[16] that began in the 1970s led to the overwhelming opinion that the main injury factor in any fall was the impact surface. This consensus of data and opinion on the main influence on injury severity (i.e. the impact surface) and the severe injuries sustained in falls led to the introduction of impact-absorbing surfaces in playgrounds all over the world. Additionally, a study was conducted on injuries sustained by children falling off beds, cribs, chairs, couches, etc. while in hospital.[17] The authors suggested that as the hospital floor is covered with hard vinyl tile, it would be of interest to study the impact of a fall on such a surface. Referring to another study[18] in which head injury severity values from tests on various playground surfaces were given, they suggest that studies should be carried out on various types of flooring and carpeting. Further research on the impact-absorbing qualities of surfaces has since been published.[3,10] The author[10] suggested in a 2006 publication that "the potential of a surface to cause head injury is dependent on the entire surface mixture, including the top surface layer (e.g. carpet and underlay), the underlying surface (wood, chipboard or concrete) and the support material (joists, supports, etc.)".

A range of standards were developed internationally to test playground surfaces, giving the heights at which a head-first fall would be expected to cause fatal head injury to a child. Manufacturers of playground surfaces provide consumers with a CFH for each of their surfaces, which is defined as "the greatest height of head-first fall from which a child, landing on a surface, could be expected to avoid sustaining critical injury".[19] This is essential so that playground designers can install the correct surfacing under equipment, safe in the knowledge that if a child were to fall from the maximum height of that equipment, the surfacing should ensure that he or she does not sustain critical injury.

The testing device stipulated by the standard[19] was selected to simulate the effective mass of a head-first impact and record an HIC score on impact. The headform was used because it is easily reproduced and has been shown to provide reasonably repeatable results.

However, further research to improve the biofidelity of a method to assess the impact-absorbing qualities of surface mixtures suggested that a biofidelic skin covering be added to the headform to improve biofidelity (human-like mechanical response).[10] The more biofidelic method was applied to assessing CFHs of common surface mixtures in domestic settings, giving a measure of their injury potential from an engineering perspective.

Physical test devices for assessing other common fall-related injuries include arm[20] and hip fracture[21] assessment devices.

It is evident that different surface mixtures produce various CFHs, and that surfaces specifically designed for use in hospitals that also consider other design requirements (e.g. infection control) can be effective in reducing injuries sustained by falls in healthcare facilities.

Case Study – SorbaShock™ Dual-Stiffness™ Impact-absorbing Flooring for Healthcare Facilities

An impact-absorbing flooring was developed by researchers[22,23] in 1998. The aim of the flooring was to minimise the "peak force experienced by the femur during a fall-induced impact, while maintaining a maximum of 2mm of floor deflection during walking". The rigidity in the flooring during normal walking ensures safety as more compliant padded flooring (e.g. wrestling mats) can induce toe-trips and forward falls.

The designers utilised FE modelling to analyse the impact response of the flooring, and further analysis included "calculations of theoretical buckling column response, experimental quasi-static loading of full scale flooring prototypes and flooring response during walking trials".[22]

SorbaShock™, LCC (www.sorbashock.com), has a 20-year exclusive lisence from the University of Notre Dame for the flooring, and a third-generation tile will be produced in 2008. The Dual-Stiffness™

Figure 3: Mathematics Dynamics Modelling Facet Full Human Body Model Simulating a Fall Down a Standard Straight Staircase

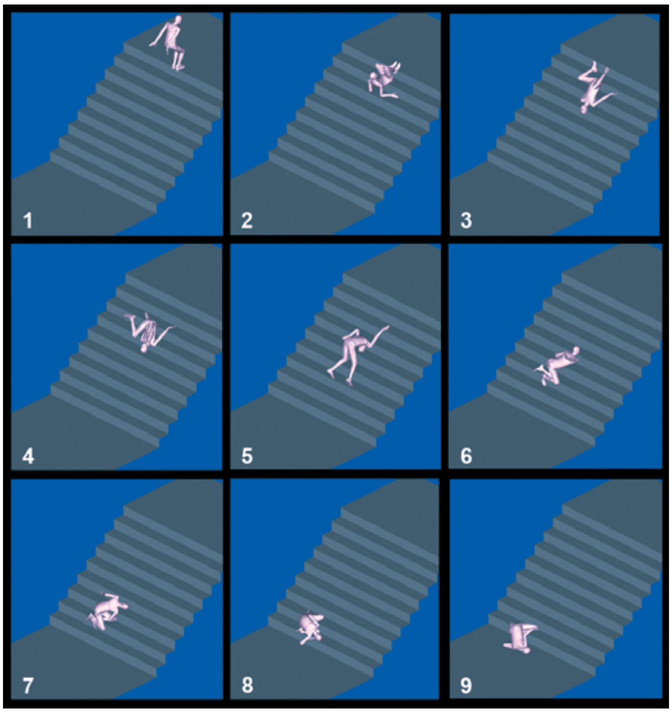
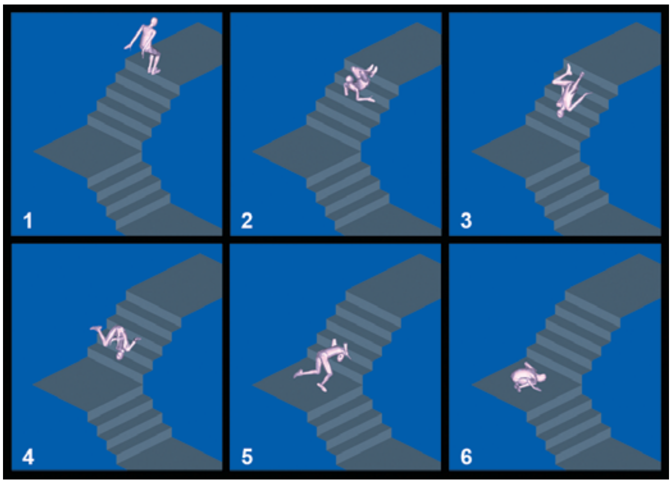


Figure 4: Mathematics Dynamics Modelling Facet Full Human Body Model Simulating a Fall Down a Quarter Landing Staircase

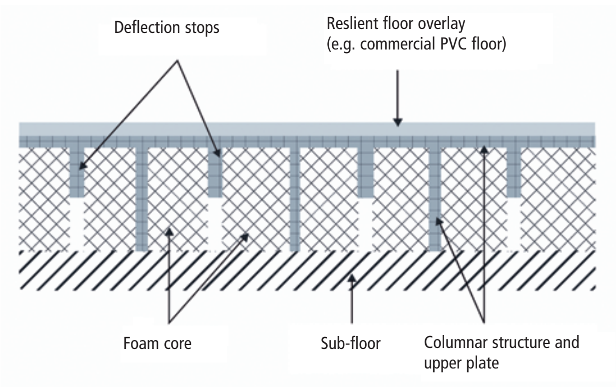


SorbaShock technology is a 300x300mm subfloor tile that comprises a shock-absorbing columnar structure integrally attached to an upper plate where the columns remain unbuckled up to a pre-determined impact load and then buckle as the load increases. The columns are encapsulated in a polymer foam material, whose stiffness controls the buckling load and post-buckling deformation of the columns. Deflection stops prevent over-buckling and/or permanent deformation of the columns (see *Figure 5*).

Potential Applications in Healthcare Facility Design

Various techniques to reduce injury severity in environments where fall risk is high have been highlighted. This article skims the surface of what can be achieved but aims to stimulate discussion and explore the application of injury biomechanics to designing safer healthcare facilities. Below are summaries of potential areas for application.

Figure 5: SorbaShock™



US and Patent Co-operation Treaty patents pending.[24]

Human Body Modelling

Human body models are a relatively new tool in injury biomechanics and the author suggests there are many more applications for these models than are currently being utilised. The simulation shown in *Figures 3* and *4* illustrates one example of how they can be used, but they can be applied to any scenario where it is necessary to investigate the blunt impact injury potential of a design. Falls are a serious problem in healthcare facilities and the human body models can be utilised to assess any scenario where a fall is likely to occur and design modifications are possible. A range of scenarios can be modelled to ensure foreseeable eventualities are accounted for, i.e. initial fall conditions, body shape, muscle activation, etc. The design can be altered and the same scenarios re-simulated to provide injury predictions for the modified design. Where specific injury predictions are necessary (e.g. hip fractures, wrist fractures, head injuries, etc.), detailed segment models can be used to assess the scenario in more detail.

Physical Impact Testing

In healthcare facilities, in areas where injury rates (related to impact with the floor) are high, biomechanical models of the head, arm and hip can be used to test the floor surface *in situ*. These tests can determine the CFH for the surface to ascertain whether the flooring currently installed in the high-risk area is providing effective protection from injury. If these CFHs are low (i.e. a critical injury could be sustained from a low fall height onto that surface), reducing the height of beds in this area could be considered. For example, a reduction in bed height of 10cm could potentially reduce a head injury from critical to moderate. If this is not feasible due to other constraints, the CFH of the surface could be increased by installing surfacing specifically designed to reduce injury potential.

Impact-absorbent Flooring

Research on playground falls suggests that impact-absorbing surfaces are essential to reduce head injury and arm fracture in children. It follows that a similar solution should be available for children and the elderly in healthcare facilities in areas where falls are likely to occur. Evidence has shown that different surface mixtures provide different impact-absorbing qualities.[3,10] Various manufacturers are beginning to develop impact absorbing flooring for hospitals.[3] It is outside the scope of this article to assess the potential cost benefits of various surfacing materials, but it is suggested that, where necessary, this type of surfacing should be considered as it can undoubtedly reduce the incidence of fractures in healthcare facilities as it has already done in playgrounds.

Concluding Remarks

The specialist area of injury biomechanics has been utilised for many years for various products and environments to investigate and alleviate injury potential outside of healthcare facilities. The author suggests that healthcare professionals should consider the application of this rapidly advancing technology to healthcare facilities design in line with the recommendations of the Design for Patient Safety Report 2003.[1] ■

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