Evaluation of Current Methods Protecting Balloon Passengers during Landings using Numerical Human Models

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Each balloon operator provides guidance on the passenger position to be adopted when landing and a number of them also apply extra protective measures, but none have been subjected to scientific scrutiny. The objectives of this study are to evaluate current methods for protecting passengers of hot-air balloons during landings by numerical simulations and to propose possible improvements.
Information about balloon accidents, passenger injuries, basket designs and passenger landing positions was gathered from literature, UK accident databases, and information from balloon operators. This information was used to make a choice in the landing situations and the protective measures that were simulated.
With this research more insight was gained in the human body kinematics during a balloon landing, the effect of landing positions and protection strategies. More research is needed to model the deformation of the basket, the effect of skids and the foam padding more realistically. The MADYMO human model showed to be applicable for balloon impact situations. Although, the MADYMO human model is originally developed for automotive impact situations, this model can be considered as a very useful tool to evaluate passenger positions and protection measures also in other aircraft during a survivable crash or emergency landing.

INTRODUCTION

The numbers of accidents and fatal accidents of hot-air balloons are one of the lowest of all aircraft types, see Figure 1. However, the accident rate and fatality rate (per 100.000 flown hours) of a hot-air balloon are the highest of all aircraft types, see Figure 2. This is due to the fact that hot-air balloons make relatively short flights with respect to other aircraft and when an accident happens it is usually during the landing phase.

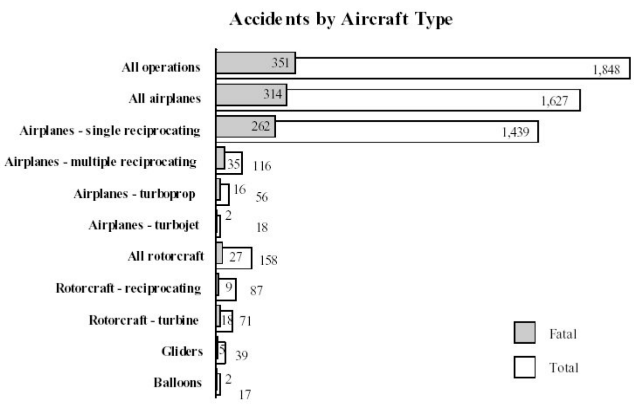


Figure 1: Number of accidents and fatal accidents by aircraft type in the United States in 1997 (NTSB 2000).

The majority of the balloon accidents in which injuries are sustained are caused by hard landings. During hard landings, contact with other passengers, contact with equipment inside the basket, contact with the ground while inside the basket or getting thrown out of the basket can lead to injuries. Hard landings are often caused by increased surface wind speed and/or gusting. Changing weather conditions are unavoidable and not always foreseen. Therefore, sufficient protection of the passengers during the landing is of major importance.

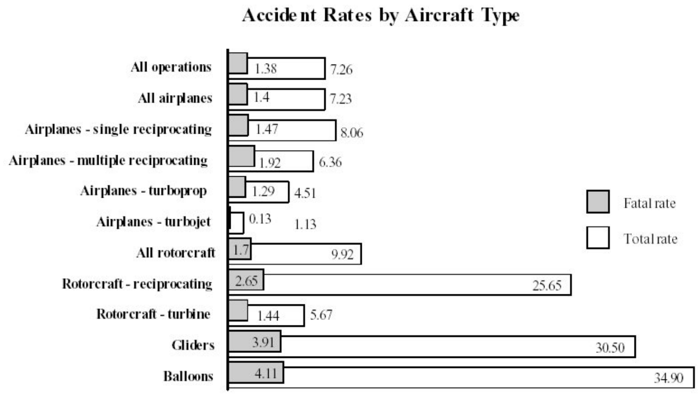


Figure 2: Accident rates and fatal rates per 100.000 hours flown by aircraft type in the United States in 1997 (NTSB, 2000).

At the time of the study (2004) there were 77 holders of Air Operator Certificate Balloons (AOCB) in the UK operating a total of 234 hot-air balloons. Of these, 169 were of a size where it is usual to operate with a basket divided into compartments, offering the advantage that the passengers can be separated from the propane cylinders and the balloon controls. Some of these baskets can carry up to 21 people. Each operator provides guidance on the passenger position to be adopted when landing and a number of them also apply extra protective measures (i.e. padding), but none have been subjected to scientific scrutiny. Therefore, the Safety Regulation Group of the Civil Aviation Authority wishes to develop advice for balloon operators on the best methods protecting passengers during landings.

The objectives of this study are to evaluate current methods for protecting passengers of hot-air balloons during landings by numerical simulations and to propose possible improvements. The protection methods include the passenger landing positions as well as the protective measures inside the basket.

METHODS

Review and Definition

First, a review of balloon accidents, passenger injuries, basket designs and passenger landing positions was performed. For this review information was used from literature, UK accident databases, and information from balloon operators. From the review the following was to be defined:

- Typical landing scenarios in which passenger injuries are most likely to occur.
- Most common passenger injuries sustained during landings.
- Safest and least safe basket types.
- Typical landing positions adopted during the landing.

A ranking was made of the landing scenarios, landing positions and basket types according to the associated risk of injury. This ranking was used to make a choice in the situations to be simulated.

To get an indication of the accelerations, and deformations of the basket during the landings, landing experiments were performed. For modelling the baskets, relevant material parameters were gathered.

Evaluation of Current Passenger Landing Positions

In the second part of this study the current passenger landing positions were evaluated by means of numerical simulations in the software package MADYMO (MADYMO 2003). Simulations were performed of the four landing scenarios with the highest risk of injury with the most and least safe basket types defined in the first part. Mathematical human computer models were used to model the passengers. For each case the human models were positioned in two different landing positions in separate simulations. Several human models were placed inside each basket model, which makes it possible to study the injuries resulting from contact with other passengers, besides those resulting from contact with the basket.

The responses predicted by the human models were compared with known injury criteria and limits to assess the risk of injury in the various landing configurations. The human model injury values resulting from the two different landing positions in the two different basket models were compared with each other to assess the safest landing position for each of the two basket types.

Evaluation of Current Protection Measures

In the third part of this study various protection measures used by some of the balloon operators were evaluated. Simulations were performed of the four most dangerous landing scenarios for the most and least safe basket types. The human models were positioned in the landing positions that showed to be the safest in the second part of this study.

The effect of the protection measures on the injury risk was assessed by comparing the human model injury values resulting from the simulations with the protection measure to that without.

RESULTS

Review and Definition

Literature

The definitions of *minor*, *serious* and *fatal injuries* used in this study are according to the International Civil Aviation Organization (ICAO), Annex 13.
It must be noted that all the literature found (Marcus *et al.* 1981, Frankenfield and Baker 1994, Cowl *et al.* 1998, Hamilton 2001) was about US balloon accident data, and that the situation in the UK could be different. From the literature the following was found about the US situation that is of note for this study:

- Most of the hot-air balloon accidents were caused during the landing.
- Collision with the ground accounted for the majority of the severe injuries.
- Other objects that form a potential danger during the landing or the landing approach are power lines, trees, fences, buildings and vertical terrain.
- The most common serious injury was a fracture of the leg.

UK Accident Databases

Databases of UK hot-air balloon accidents found were from the CAA, the Air Accidents Investigation Branch (AAIB) and the BBAC. All the accidents described in the CAA database, the AAIB bulletins and BBAC reports that happened between January 1993 and January 2003 were reviewed. The total number of records was 61. Only 3 fatal accidents were reported, and all three were caused by power-line contact. In 70% of the accidents minor and/or serious injuries were sustained, of which 70% were caused by hard landings. The UK accident databases complied with the literature findings. The accidents caused by hard landings in which injuries were sustained (30 records) were reviewed further on the landing scenario, types of injuries, type of basket and passenger landing positions.

Landing Scenarios

The four landing scenarios with the highest risk of injury according to the UK accident databases complied with the opinions of the six questioned UK balloon operators. The definitions of these landing scenarios are given in Table 1.

Table 1: Definitions of the landing scenarios that were simulated.

Landing scenario	Horizontal speed	Descent rate
Heavy landing	10 knots (5,14 m/s)	500 feet/min. (2,54 m/s)
Tip-over	10 knots (5,14 m/s)	300 feet/min. (1,52 m/s)
Contact obstacle with whole basket front side	8 knots (4,11 m/s)	100 feet/min. (0,51 m/s)
Contact obstacle at a corner of basket	8 knots (4,11 m/s)	100 feet/min. (0,51 m/s)

Injuries

In the UK accident databases, at least 54% of the serious injuries caused by hard landings were fractures of the lower extremities (at least, because not specified serious injuries were counted as other serious injury). The various injuries that were sustained in order of occurrence were: broken leg (femur or tibia), broken ankle, sprained ankle, broken arm, bruises and grazes, broken rib, knee injury, fractured pelvis, broken bone in foot, back injury, shoulder ligament injury, bruising shoulder, cut hand and head impact.

Basket Types

To conclude what type of basket has the highest injury risk the number of flights for each type of basket in the UK would need to be known. However, in the UK, neither the basket types nor the number of flights are registered in a national database, and no other information source was available. According to the balloon operators involved in this study the double T-partitioned basket is the most widely used basket for commercial passenger flights. Given the low number of serious injuries for this basket, the double T-partitioned basket was modelled to represent the safest basket type. The open basket had the highest number of serious injuries, and was therefore modelled to represent the least safe basket.

Landing Positions

There was no information found in the literature and little in the UK databases about the passenger landing positions. Therefore, balloon operators from 6 different UK ballooning companies as well as the commercial balloon operators present at the Bristol Balloon Fiesta 2003 were asked about the passenger landing positions instructed to their passengers. It became clear that the instructions depend on the type and size of the basket, but also on the insight of the pilot. However, all pilots instruct the passengers to have their knees slightly bent, keep a small distance between the feet and hold onto the rope handles and/or a fuel cylinder. The most common instructed passenger positions for the open and double T-partitioned baskets are described below.

<u>Open basket</u>:

1. <u>The backward position</u>: two passengers are at the front of the basket in a sideways position back to back between the cylinders, and two passengers are at the back side by side between the cylinders with their backs in travel direction.
2. <u>The sideways position</u>: all four passengers are at the front of the basket with their left arm/shoulder against the front side facing the pilot with all four cylinders at the backside.

<u>Double T-partitioned basket</u>:

1. <u>The backward position</u>: the front passengers lean with their backs against the basket front side and the back passengers against the partition in travel direction.
2. <u>The sideways position</u>: the front passengers lean with their arm/shoulder against the basket front side and the back passengers against the partition in travel direction, all facing the pilot in the middle of the basket. The outside passengers also lean with their backs against the left or right basket sides.

Landing Experiments

To get an indication of the accelerations and deformations of the basket during the landings, real-life landing experiments were performed. Three acceleration load cells were placed into three perpendicular directions fixed to the basket ground-plate at the front of the bottom plate (landing side). The amplifier and the data recorder were placed in the basket in a way that they were protected against impacts. The pilot tried to imitate different landing scenarios.

The maximum horizontal landing speed was 4.1 knots (2.1 m/s), and the maximum vertical landing speed was 560 ft/min (2.8 m/s). The highest peak accelerations measured were for forward 90 m/s^2, lateral 70 m/s^2 and downward 125 m/s^2. The peak accelerations had a duration of 10-20 ms. The measurements were used to validate the contact characteristic of the basket model with the ground. The basket deformation seemed to be limited, however the basket deformation might be higher at higher horizontal landing speeds and for heavier baskets.

Evaluation of Current Passenger Landing Positions

Software and Tools

To evaluate the current passenger landing positions in hot-air balloons numerical simulations were performed using MADYMO version 6.1 (MADYMO 2003 a). MADYMO provides several human and crash dummy models. For this study the 50th percentile male multi-body human model was chosen to numerically model the passengers (MADYMO 2003 b). In this human model various detailed segments can be included. The detailed segments provide more detailed information, and some can simulate muscle activity. Since leg injuries are most common in balloon accidents, two detailed legs were included in the human model for this study, see Figure 3. The leg model is especially developed and validated for impact loading under the foot. In addition, this model is able to simulate leg muscle activity, which is crucial for simulating a standing position with the knees slightly bent.

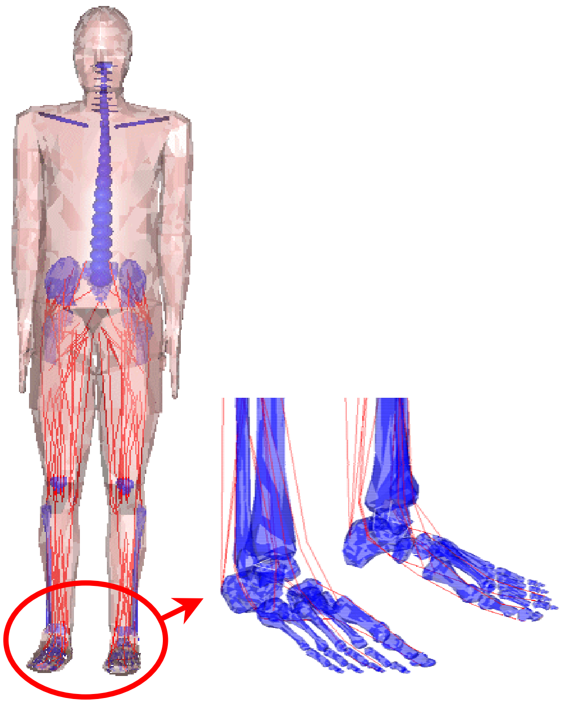


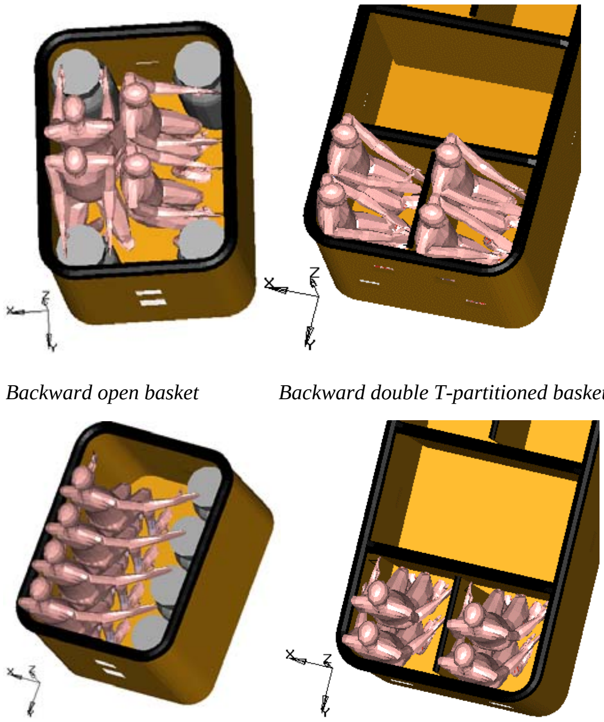
Figure 3: Left: MADYMO multi-body model with detailed legs left. Right: close up of the bones, ligaments and muscles in the feet.

Basket Model

The geometries and masses of the baskets, including the top frame padding, and fuel cylinders were provided by Lindstrand Ltd. The basket as well as the cylinder geometries were converted to a rigid FE MADYMO model. Rope handles were modelled at positions in the basket models as provided by the manufacturer. The open basket model was equipped with four cylinders, each with a full weight. The cylinders were rigidly connected to the basket model. In a double T-partitioned basket the cylinders are in the middle compartment, separated from the passengers. The cylinders in the double T-partitioned basket were not modelled, but their weights and inertia was compensated for in the model. The two basket models are shown in Figure 4.

Positioning of Human Models

Four human models were positioned in each basket by performing a pre-simulation, in order to get the human models in a stable state with themselves and their environment. In this pre-simulation of 500 ms the human models were initially positioned with their knees bend and fixed at 45° with the vertical and their feet 1 cm above the basket bottom plate. During the pre-simulation the human models moved downwards by the effect of gravity. The basket was fixed to the ground. The heads, vertebrae, hips and ankles were restrained in a landing position. The hands were attached to the rope handles (two tension-only elements per hand). In this way natural positions for the arms and ankles were obtained. The ligament strains and the new joint positions resulting from the pre-simulation were inserted as initial conditions in the landing simulations. The backward and sideways landing positions of the human models in the open and double T-partitioned basket model are shown in Figure 4. The weight and inertia of the pilots and the four passengers that were not represented by human models was compensated for in the model. The pilot was not modelled, since to investigate the safety of the pilot is not the aim of this study, and thereby, it will make the simulations too complicated.



Backward open basket *Backward double T-partitioned basket*

Sideways in open basket *Sideways in double T-partitioned basket*

Figure 4: Numerical models of passengers in landing positions.

Leg Muscle Activity

In order to keep the human models in a standing position muscle activity was prescribed to the legs. The amount of activity for each muscle was obtained from an experimental-numerical study about jumping (Spägele *et al.* 1999). It was assumed that the leg muscle activity at the end of the landing phase of a jump would be comparable to the situation of a standing position with the knees slightly bent. This was validated by performing a simulation of 200 ms in which the human models stood in the basket in the landing position under gravity. That the human models stayed in their initial position during the whole simulation confirms that the leg muscle activity applied is realistic.

Boundary Conditions

First the landing experiments were simulated with the open basket using the measured horizontal and vertical velocities as initial conditions. The full basket mass was made equal to the full mass of the basket used for the landing experiments. The contact characteristic between the basket and the ground was validated by comparing the measured with the calculated basket accelerations.

The four different landing scenarios were simulated by prescribing the forward and downward velocities as defined in Table 1 as initial conditions to the basket, the cylinders, the pilot and the passengers. Also gravity was prescribed. At time zero the basket was 20 mm above the ground in all landing scenarios. Contacts between the basket, the ground, the partitions and the human models were described by stress-strain characteristics. In the 'obstacle' and 'obstacle at corner' landing simulations a low stone hedge was modelled with which the basket made contact just before contacting the ground. The landing scenarios were each simulated for 200 ms. The contact with the ground and/or the obstacle decelerates the basket in horizontal and vertical direction resulting in impacts to the human models wherever they contact the basket or each other.

Injury Criteria

For evaluation of the safety of the landing positions the injury values from the simulation output were compared. The injury criteria that were chosen were based on the passenger injuries according to the UK databases and the impact situations during balloon landings. The injury criteria that were chosen and the tolerance limits from literature are given in Table 2.

Table 2: Injury criteria and tolerance limits used to evaluate the safety of the passenger landing positions.

Injury	**Injury Criterion**	**Tolerance Limit**	**Reference**
Femur fracture	Transverse femur bending moment	320 Nm	Kress *et al.* 1993
Tibia fracture	Lower tibia compression force	7.8 kN	Begeman & Prasad 1990
Ankle fracture	Lower tibia dorsiflexion torque	60 Nm	Portier *et al.* 1997
Ankle sprain	Anterior talofibular ligament strain	50 %	Attarian *et al.* 1985, Siegler
	Posterior talofibular ligament strain	50 %	
	Calcaneofibular ligament strain	50 %	
Head injury	Resultant head angular acceleration	1800 rad/s^2	Ommaya *et al.* 1967
	Resultant head linear acceleration	1000 m/s^2	Versace 1971

Simulation Results

Since, there were some unknown parameters concerning the basket, the injury criteria values cannot be interpreted as an indication for injury directly. However, the calculated maximum injury criteria values were around the injury tolerance levels, indicating that injuries are likely to occur at the landing velocities that were simulated which corresponds to the accident database.

For an easy comparison of the different landing positions a relative value for the injury risk was calculated for each kind of injury (femur fracture, tibia fracture, ankle fracture, ankle sprain and concussion) for each landing scenario. For this, the maximum injury criteria values resulting from all the passengers were first made relative. This was done by dividing each maximum injury criterion value of each simulation by the one calculated for the double T-partitioned basket backward position for the same landing scenario. Thus, the relative injury values for all the simulations with the double T-partitioned basket and the human models in backward position become 1. The double T-partitioned basket with the human models in backward position was chosen as reference, because most balloonists think this is the safest situation. In order to compare the overall safety of each landing position per landing scenario, a relative value for the total of injuries was calculated. This value was defined as the mean of the five relative injury values, with each kind of injury counted for the same amount.

It must be noted that the relative values for the injury risks can only be compared qualitatively. Thus, a relative injury value of 1.2 for a certain position in a certain basket does not mean that the chance on an injury is 20% higher than for the backward position in the double T-partitioned basket, but only means that the injury risk is higher.

From parameter variation simulations (robustness tests) it was decided to choose a significance level of 25% to evaluate the effect of the passenger landing positions and the protection measures on the injury criteria values.

Figure 5 shows the relative value for the total of injuries for all the landing position simulations. Figure 5 shows that the sideways position in the open basket is significantly safer than the backward position in the 'tip-over' landing, but the backward position is significantly safer in the 'obstacle' landing. For the double T-partitioned basket the results suggest that the backward position is significantly safer in the 'heavy' landing, but there is no significant difference in the other landing scenarios.

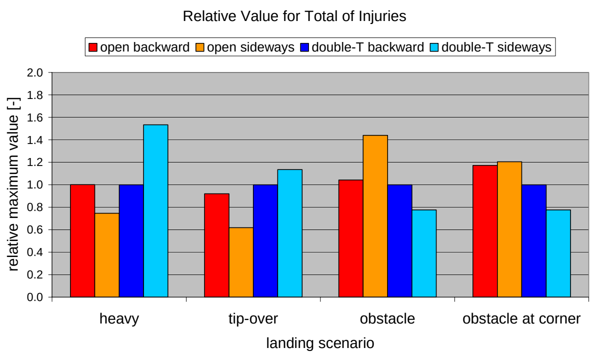


Figure 5: Relative maximum value for the total of injuries resulting from the landing position simulations.

Evaluation of Current Protection Strategies

Current Protection Strategies

Information about current protection strategies was gained from the UK balloon operators and the UK ballooning companies that were involved in this study. The following protection measures were evaluated:

- Skids under the basket: Skids would decrease the friction between the ground and the basket during the landing, which decreases the landing deceleration in horizontal direction. Skids would also have a damping effect in vertical direction due to that the skids dig into the ground. Thereby, reducing the horizontal deceleration decreases the chances of a 'tip-over' landing.
- Foam padding in the basket: Foam padding on the floor would reduce the impact under the feet during the landing. Foam padding at the inner sides would reduce the impact on the back and shoulders. Foam padding on the rim would reduce the impact on the back, shoulders and head.
- Other passenger landing postures:
  - Knees more bent than 45º with vertical: The passengers have their knees bent during the landing such that their neck is in the rim padding which would reduce the head accelerations.
  - A foam block for the passengers to sit on during the landing would decrease the impact loading under the feet.

Skids under the Basket

Skids under the basket were modelled by simply reducing the friction between the basket and the ground. The digging of the skids into the ground was not modelled, since there were no data available. The skids were simulated for the 'heavy' landing only, since the effects of skids reduce the chances of a tip-over landing and during an obstacle hit the skids do not have any effect.

The simulation results showed that the skids seemed to have a negligible effect on the injury criteria values. However, the real effect of skids on the landing deceleration and basket rotation is not known. To study the real effects of skids on the basket movement, experimental testing is needed.

Foam Padding

For the floor, inner sides and rim of the basket different types of foam padding are applied. The specifications of the foam padding were provided by Lindstrand Ltd.. The thickness and the stress-strain characteristic of the foam padding were incorporated in the contact definition between the human models and the basket model. The coverings of the foam padding were not modelled.

The effect of the foam padding on the relative value for the total of injuries for all the landing scenarios is shown in Figure 6. Figure 6 shows that foam padding decreased the relative value for the total of injuries for the double T-partitioned basket in the backward position by about 40% in all landing scenarios. For the double T-partitioned basket the foam padding decreased almost all injury criteria values for all landing scenarios. In case of the open basket the foam padding decreased the relative value for the total of injuries by more than 60% in the 'obstacle' landing and by more than 30% in the 'obstacle at corner' landing. However, the foam padding did not significantly change the relative value for the total of injuries for the open basket in the 'heavy' and 'tip-over' landings.

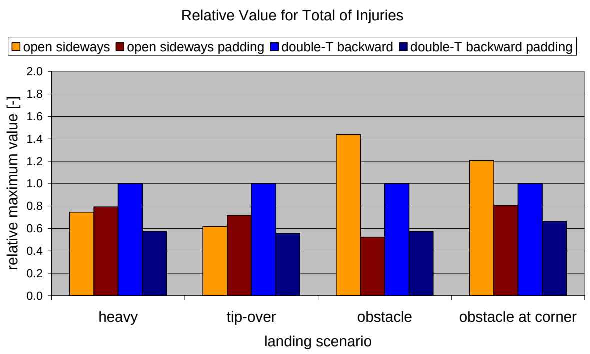


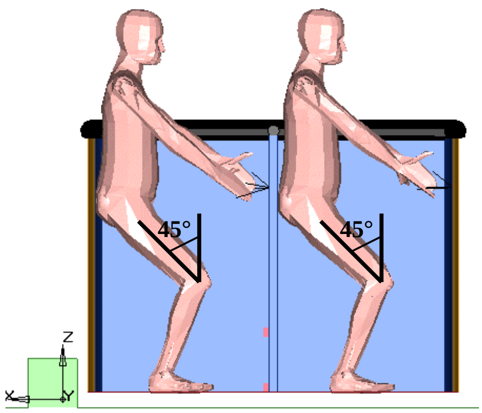
Figure 6: Relative maximum injury value for the total of injuries resulting from the original simulations and the simulations with foam padding modelled

Other Passenger Landing Postures

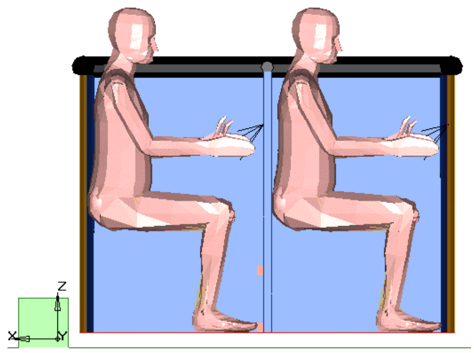
Variations in the passenger landing postures were only made for the backward position in the double T-partitioned basket with foam padding. The two variations in posture and the original backward landing position in the double T-partitioned basket are shown in Figure 7.

The specifications of the foam block were provided by Lindstrand Ltd.. The thickness and the stress-strain characteristic of the foam block were incorporated in the contact definition between the human models and the foam block. In reality, the foam blocks are covered by a cordura fabric to protect the foam against wear and tear. Like for the foam padding, the coverings of the foam blocks were not modelled.

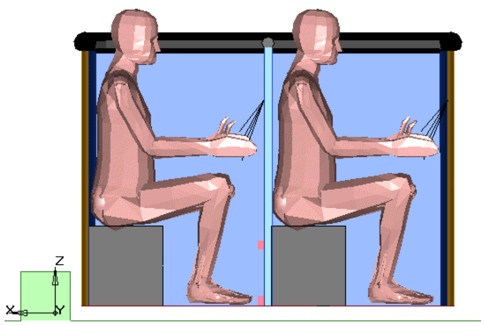
In the simulations in which the human models had their knees more bent the leg muscle activity was the same as in the original simulations. The muscles of the human models sitting on a foam block were not activated, simulating a relaxed seating position.



Original backward position



Knees more bent



Seated on foam blocks

Figure 7: Simulated passenger landing postures in backward landing positions.

The effect of the two different landing positions on the relative value for the total of injuries for all the landing scenarios is shown in Figure 8. Figure 8 shows that both the different landing positions change the relative value for the total of injuries compared to the original landing position for less than 25% for all landing scenarios, except the foam block decreased the relative value for the total of injuries for 25% in the obstacle landing. However, for both the different landing positions the relative injury values for a broken femur and broken tibia were significantly decreased for the 'tip-over', 'obstacle' and 'obstacle at corner' landings. The foam block also significantly decreased the relative injury value for a broken ankle for these landing scenarios. However, the foam block significantly increased the relative injury value for concussion for all landing scenarios. This was caused by that the heads of the passengers were at height of the basket rim. Consequently, their heads were impacted against the basket rim. In the position with the knees bent at 90º the relative injury value for a sprained ankle was significantly increased for all landing scenarios. The relative injury value for concussion was significantly increased in the ‘obstacle at corner’ landing.

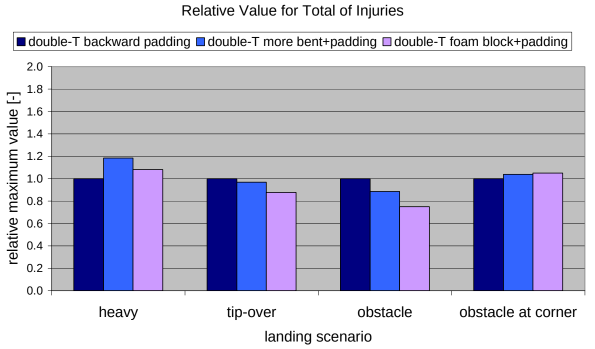


Figure 8: Relative maximum injury value for the total of injuries resulting from the simulations with foam padding, the simulations in which the passengers have their knees more bent, and the simulations in which the passengers are seated on a foam block.

CONCLUSIONS

With this research more insight was gained in the human body kinematics during a balloon landing, the effect of landing positions and protection strategies. More research is needed to model the deformation of the basket, the effect of skids and the foam padding more realistically.

The MADYMO human model showed to be applicable for balloon impact situations. Although, the MADYMO human model is originally developed for automotive impact situations, this model can be considered as a very useful tool to evaluate passenger positions and protection measures also in other aircraft during a survivable crash or emergency landing.

ACKNOWLEDGEMENTS

This study is conducted with the help of many people that are involved in the ballooning business. The authors would especially like to thank Simon Forse, Shiralee Colin, Wyn Morgan, Phil Hossack, Tony Pinner, Kenneth Karlström, John Davies, Tim Parker, Tony Brown, Tom Sage, Rob Cox, Johannes Kooistra and Berend Jan and Sabina Floor for their voluntary contribution to this research.

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