Safety Regulation Group

Civil Aviation Authority

CAA Paper No. 2006/06

Evaluation of and Possible Improvements to Current Methods for Protecting Hot-Air Balloon Passengers During Landings

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Evaluation of and Possible Improvements to Current Methods for Protecting Hot-Air Balloon Passengers During Landings

Report prepared for the CAA by TNO, Delft, The Netherlands

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Summary

The guidance that hot-air balloon operators provide on the passenger position to be adopted during landing varies and none have been subjected to scientific scrutiny. Therefore, the Safety Regulation Group of the Civil Aviation Authority wished to develop advice for balloon operators on the best methods to protect passengers during landings.

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

In the first part of the study a review of balloon landings, passenger positions and basket designs and the risk of injury was performed. For this review information was used from literature, UK accident databases, and questionnaires to balloon operators. The results from the review were used to make a choice in the situations that were to be simulated in the second part of this study. In the third part of this study various protection strategies already used by some of the balloon operators were evaluated.

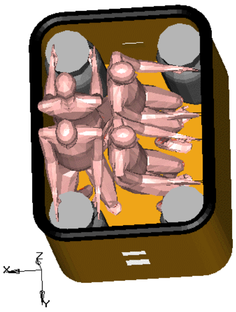
The only literature found was about balloon accidents in the US. Information about UK balloon accidents was found in UK databases. The UK accidents comply with the literature findings on the main cause of balloon accidents (landing), the main cause of the serious injuries (collision with the ground), and the most common injury (fractured lower extremity).

According to the UK databases the three landing scenarios in which the most serious injuries were sustained are a heavy landing of the basket on the ground, tip-over of the basket and when the basket contacts a fence or hedge during a drag. All six balloon operators that were questioned by TNO also said that the heavy landing is the most dangerous landing situation for the passengers. The four other dangerous landing scenarios described by the balloon operators (bouncing drag landing, tip-over of basket, contact with an obstacle, twisting of the basket) agreed with the most dangerous landing scenarios according to the UK databases.

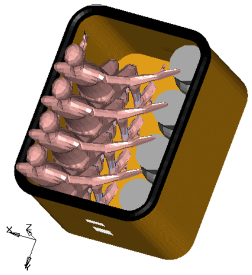
The most serious injuries were sustained in open baskets, and the second most in single T-partitioned baskets according to the UK databases. The injury risk cannot be evaluated, since the number of each type of basket used in the UK is not known. From the six questioned balloon operators the double T-partitioned basket was most used, and secondly the open basket. It was decided by all the parties involved in this project to model an open basket that can carry four passengers plus a pilot and to model a double T-partitioned basket that can carry eight passengers and two pilots.

From questionnaires to the six balloon operators and from interviews with many commercial pilots at the Bristol Balloon Fiesta 2003, it can be concluded that the current passenger landing position depends on the basket type, basket size and the pilot's opinion. The most common passenger landing positions for the open basket are:

- The backward position: 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.

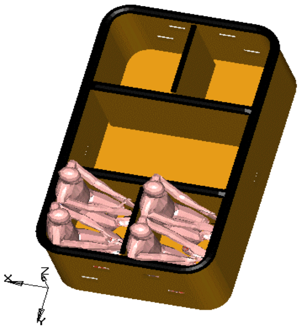


- The sideways position: all four passengers are at the front of the basket with their left arm/ shoulder against the front side with all four cylinders at the backside.

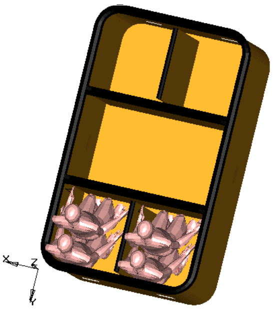


The most common passenger landing positions for the double T-partitioned basket are:

- The backward position: the two front passengers lean with their backs against the basket front side and the back passengers against the partition in travel direction.



- The sideways position: the two 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.



In the second part of the study a flat-top open basket carrying four passengers, a pilot and four cylinders was modelled in the software package MADYMO. Also a double T-partitioned basket carrying eight passengers, one pilot and four cylinders was modelled. In each basket four of the passengers were modelled by human models with detailed leg information. The following four landing scenarios were numerically simulated: 1) heavy landing, 2) tip-over landing, 3) contacting an obstacle during landing, and 4) contacting an obstacle at a corner of the basket during landing. The passenger positions that were numerically simulated were: 1) backward, and 2) sideways to the travel direction. The landing scenarios were simulated by prescribing the forward and downward velocities of the basket, and defining contact between the basket and the ground and the basket and the obstacle. The resulting basket accelerations were validated with data from real-live landing tests. To evaluate the safety of the landing positions, the calculated relative injury risks for a broken femur, broken tibia, broken ankle, sprained ankle and head injury (concussion) for all the simulations with the different landing positions were compared.

In the third part of this study the following protection strategies were evaluated for the safest landing positions: 1) skids under the basket, 2) foam padding in the basket, and 3) different passenger landing positions (knees more bent and seating on a foam block). These protection strategies were chosen because the UK balloon operators experience is that these reduce the chance of injuries. Information about current protection strategies was gained from the UK balloon operators and the UK ballooning companies that assisted in this study. To evaluate the effect of each protection strategy on the injury risk, the calculated relative injury risks for a broken femur, broken tibia, broken ankle, sprained ankle and concussion for the protection strategy simulations were compared to that of the same simulations without the extra protection.

From the simulation results and the review of the current methods to protect the passengers during balloon landings the following is recommended:

- For the passengers in an open basket it is recommended to adopt a sideways landing position at the front side of the basket with the fuel cylinders installed at the back of the basket.
- For passengers in a double T-partitioned basket it is recommended to adopt a backwards landing position.
- It is recommended to let the most vulnerable passenger in an open basket in a sideways position be at the front of the row of passengers and the strongest at the back.
- Although counter-intuitive, it is recommended to let the most vulnerable (age, build) passengers in a double T-partitioned basket be in the front compartments of the basket and the strongest passengers in the back compartments.
- For both the sideways landing position in the open basket and the backwards landing position in the double T-partitioned basket, it is recommended for the passengers to bend their knees, but less than 90 degrees.
- It is highly recommended to apply foam padding to the basket floor, inner sides and rim.
- For passengers in a backward seating position on a foam block, it is recommended to apply extra protection to the basket that decreases the impact loading to the head from contact with the basket side/rim.

The following is recommended for further research on protecting passengers during balloon landings:

- To also model the most common most flexible basket for the cases simulated in this study. If the results of these simulations show that the above recommendations also count for the flexible basket, these recommendations can be used to develop advice for balloon operators on the best methods protecting passengers during landings.
- To test the real effects of skids on the movement of the basket experimentally and study the effects of skids on the passengers' safety by numerical simulations.
- To optimise the injury reduction of the foam padding (density, energy absorption, and thickness) at the basket floor, inner sides and rim by using finite element simulations.
- To optimise the seating height and seating position of the passengers by numerical simulations.

The first recommendation was investigated in a follow-up study (reported in Section 6). The objective of the follow-up study was to evaluate the effect of the basket flexibility on the safety of the hot-air balloon passengers during landings for the most flexible open and double T-partitioned basket that are equal to the baskets that were chosen in the first study.

Real baskets of approximately the same size as the ones that were modelled were subjected to deformation tests. The open and double T-partitioned basket models from the first study were made flexible by using finite element modelling. The force and displacement measurements from the basket deformation tests were used to find the best fitting material parameters for the flexible basket models.

Next, the rigid basket models in the simulations of the passengers in the backward and sideways landing positions in the open and double T-partitioned (without padding) were replaced by the flexible models, and the simulations were repeated. The resulting injury criteria values showed some differences with the rigid basket models. However, the conclusions as stated above were not influenced.

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Section 1 Introduction

1 Problem Definition

1.1 In the UK hot-air balloons are regulated under similar aviation regulations as every other category aircraft. In the ten years to January 2003, three fatal accidents were reported to the CAA in the UK. These three fatal accidents were all caused by the balloon making contact with electric wires after which the passengers fell from the basket and/or sustained burns. 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 flight hour of a hot-air balloon are the highest of all aircraft types, see Figure 2. This is possibly due to the fact that hot-air balloons make relatively short flights with respect to other aircraft.

1.2 The majority of the accidents in which injuries are sustained are caused by hard landings. During hard landings, contact with other passengers, contact with equipment inside the basket, collision 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.

1.3 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 normal 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, but none have been subjected to scientific scrutiny. Therefore, the Safety Regulation Group of the Civil Aviation Authority wished to develop advice for balloon operators on the best methods for protecting passengers during landings.

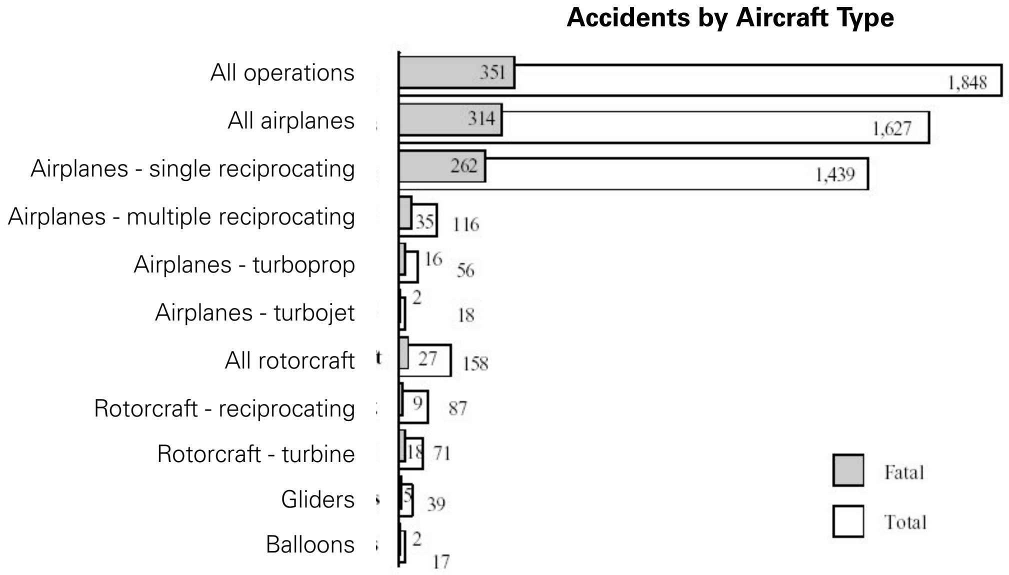


Figure 1 Number of accidents and fatal accidents by aircraft type in the United States in 1997 (NTSB 2000).

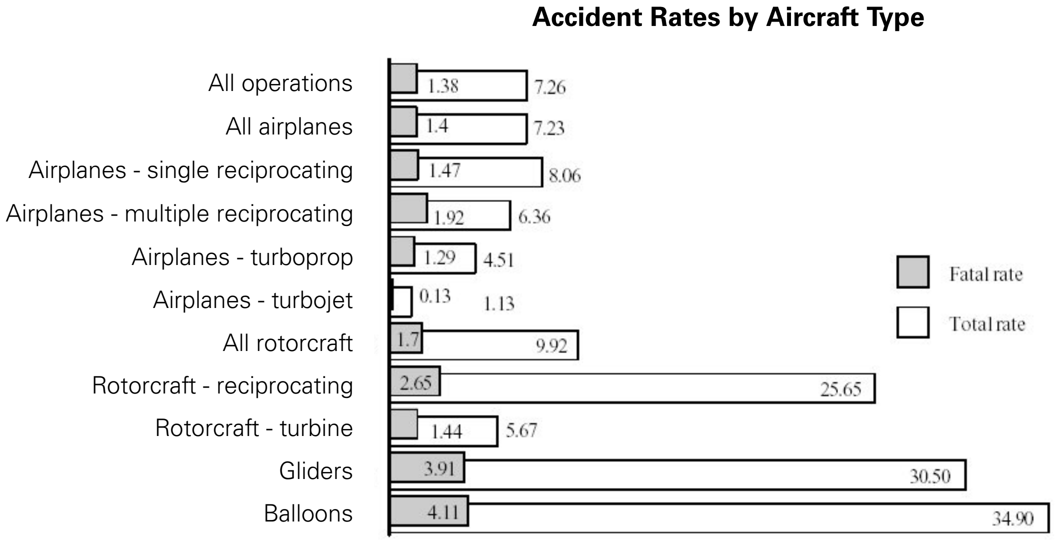


Figure 2 Accident rates and fatal rates per 100.000 hours flown by aircraft type in the United States in 1997 (NTSB, 2000).

2 Objectives

The objectives of this study were 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 in the basket.

3 Approach

3.1 Review and Definition

First, a review of balloon landings, passenger positions and basket designs and the risk of injury was performed. For this review information was used from literature, UK accident databases, and questionnaires to balloon operators. From the information the following was defined:

- Typical landing scenarios in which passenger injuries are most likely to occur.
- Most common passenger injuries experienced during landing, ranked according to severity.
- 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 that were to be simulated in the second part of this study.

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. This review and definition part of the study is described in Section 2.

3.2 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 most dangerous landing scenarios defined in the first part of this study for two basket models. The most and least safe basket types defined in the first part of this study were modelled. 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. Four 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 injury criteria and limits commonly used in traffic and aviation safety regulations 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. This part of the study including a description of the models that are used in the simulations is described in Section 3. Based on the simulation results and the review, advice is given on the safest passenger landing positions for each of the two basket types in Section 5.

3.3 Evaluation of Current Protection Strategies

In the third part of this study various protection strategies already 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 defined in the first part of this study. The human models were positioned in the landing positions that were concluded to be the safest in the second part of this study.

The effect of the protection strategies on the injury risk was assessed by comparing the human model injury values resulting from the simulations with the protection strategy to that without. This part of the study is described in Section 4. Based on the simulation results and the review, advice is given on the usage of protection strategies and potential improvements in Section 5. Also recommendations for further research on protection strategies is given in Section 5.

Section 2 Review and Definition

1 Definitions of Injury Severities

The definitions of *minor, serious* and *fatal injuries* used in this study are according to the International Civil Aviation Organization (ICAO), Annex 13:

Minor injury: An injury, other than serious or fatal, which is sustained by a person in an accident.

Serious injury: An injury which is sustained by a person in an accident and which:

- a) requires hospitalisation for more than 48 hours, commencing within seven days from the date the injury was received; or
- b) results in a fracture of any bone (except simple fractures of fingers. toes, or nose); or
- c) involves lacerations which cause severe haemorrhage, nerve, muscle or tendon damage; or
- d) involves injury to any internal organ; or
- e) involves second or third degree burns, or any burns affecting more than 5 per cent of the body surface; or
- f) involves verified exposure to infectious substances or injurious radiation.

Fatal injury: An injury, which is sustained by a person in an accident, which results in death within thirty days of the date of the accident.

2 Review on Balloon Accidents

2.1 Literature

Below, the literature found about balloon incidents and accidents is summarised. Unfortunately, none of the literature contained information about passenger landing positions.

Marcus *et al.* (1981) published a study about hot-air ballooning injuries from a surgeon's point of view. He stated that the major sites of ballooning injuries were the ankles, spine and legs.

Frankenfield and Baker (1994) published a study of the epidemiology of injuries due to hot-air balloon crashes. They examined 5 years of United States National Transport Safety Board (NTSB) crash data (1984-1988), counting 138 crashes, based on the NTSB's 2-page abbreviated reports. Crashes occurred in 66% of the cases during landing attempts. Collisions with the ground accounted for 52.3% of the hot-air balloon crashes, including 1 fatality and the majority of the severe injuries. Power lines accounted for 25.0% of the balloon collisions, trees for 7.5 %, another balloon for 5.4%, a fence for 5.0%, a pole for 2.5 % and a building for 2.3%.

Cowl *et al.* (1998) reviewed the records of the 495 hot-air balloon crashes recorded by the US Civil Aeronautics Board (1964-1967) and the NTSB (1967-1995), including statements recorded by passengers and pilot medical reports filed for injured victims. Most crashes (46%) occurred during landing attempts or while approaching a landing spot (20.6%). In 30.7% of the crashes the ground was impacted first, power lines in 27.7%, no collision in 13.3%, trees in 9.3%, building or fixed structure in 6.2%, vertical terrain in 3.8%, another balloon in 3.4%, fence in 3.2 %, and water in 1.0%. As an example of an injury sustained during a 'no collision' accident, a passenger that twisted an ankle during a landing was given. The most common serious injury was a fracture of the lower extremity, accounting for 56.3% of the serious injuries. Head injuries accounted for 9.3% of the serious injuries. The conclusion of this study was that a collision with the ground is the most significant cause of a fatality or serious injury, whereas power line contact is the most significant cause of fatality.

Hamilton (2001) reviewed NTSB's balloon final reports from a 20-year period. In this review the landing (47.8%) was also mentioned to be the major cause of the reported accidents and secondly the landing approach (21.0%). Hard landings accounted for 39.0% of the accidents and power line contacts for 30.8%.

It must be noted that all the literature found was about US balloon accident data, and that the situation in the UK could be different. From the literature the following can be concluded 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.

2.2 UK Accident Databases

Databases of UK hot-air balloon accidents found were from the CAA, the Air Accidents Investigation Branch (AAIB) and the BBAC. The CAA database is an extensive database of all accidents in which damage and/or injuries were sustained. This database provides global descriptions of the hot-air balloon accidents. The descriptions often refer to the AAIB bulletins and/or the BBAC report for more details.

All the accidents 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 injuries were sustained, of which 70% were caused by hard landings. At least 38% of the accidents were caused by collisions with the ground (heavy landing), accounting for at least 39% of the serious injuries (the landing scenario that was not specified was counted as other landing scenario). The accidents caused by hard landings were reviewed further on the landing scenario, type of basket, passenger landing positions and types of injuries. Per selected accident these four items are described in Table 1 in Appendix A.

The accidents described in Appendix A, Table 1 were divided into types of landing scenarios. The number of occurrences and the types of injuries for each type of landing scenario are given in Section 2, Table 1. The landing scenarios in Section 2, Table 1 are ranked according to the injury risk, counting the number of serious injuries first and then the number of minor injuries. The one passenger that suffered two broken legs was counted as one injury. Further, in no other case were passengers described to have suffered more than 1 injury. In one accident the injuries to the different passengers resulted from 2 different causes (23 July 1994: two passengers were thrown out on first landing by the basket turning over; at second landing the basket bounced hard causing a third passenger to be injured.). According to the UK databases from January 1993 to January 2003 the three landing scenarios in which most serious injuries were sustained are:

- Heavy landing of the basket to the ground (bouncing hard).
- Tip-over of the basket.
- Basket contacting a fence or hedge.

Table 1 Landing scenarios ranked according to injury risk

Landing scenario	Number of occurrences	Type of injuries	Injury severity
Heavy landing (basket bounces hard on ground)	12	4 broken leg (2 broken legs of 1 passenger counted as 1) 4 broken ankle 1 serious back injury 1 broken arm 1 serious injury* 5 sprained ankles 1 minor back injuries 1 minor knee injury 1 bruising shoulder 4 bruises and grazes 3 minor injuries*	11 serious 10 minor
Tip-over of basket	9	4 broken arm 2 broken tibia 1 broken rib 1 broken ankle 1 shoulder ligament injury 1 minor knee injury 2 minor injuries*	9 serious 3 minor
Contact fence or hedge	3	1 broken ankle 1 broken rib 1 cut hand and bang to head 2 minor injuries*	2 serious 3 minor
Basket not oriented correctly upon touch down (basket twists)	2	1 fractured pelvis 1 serious injury* 11 minor injuries*	2 serious 11 minor
Violent drag	2	1 broken leg 1 serious injury* 4 minor injuries*	2 serious 4 minor
Land in ditch	1	1 broken bone in foot	1 serious 0 minor
Unknown	1	1 broken ankle	1 serious 0 minor

*) Not specified in the UK databases.

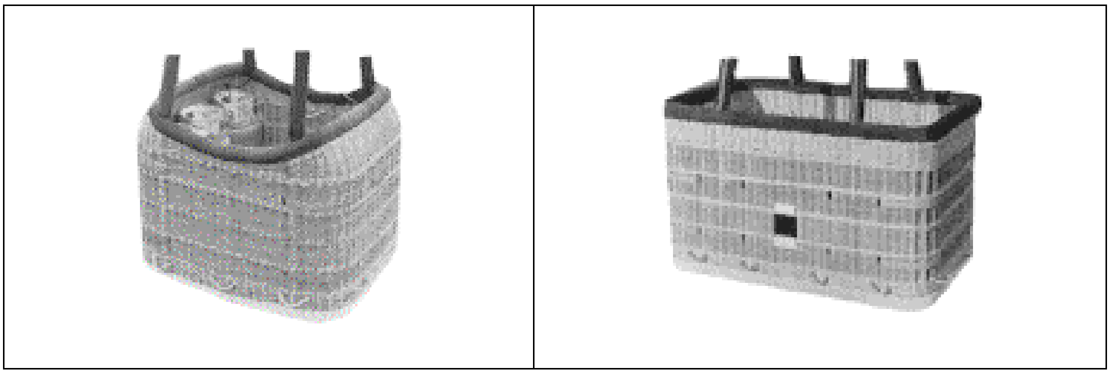


Figure 1 Open baskets. The fuel cylinders are situated in the corners or at the sides of the basket.

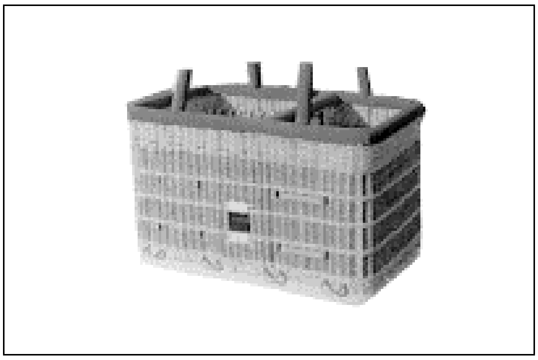


Figure 2 Single partitioned basket. The pilot and the fuel cylinders are in the small compartment separated from the passengers.

Figure 3 Mini T-partitioned basket. The fuel cylinders are in the small compartment separated from the passengers and the pilot.

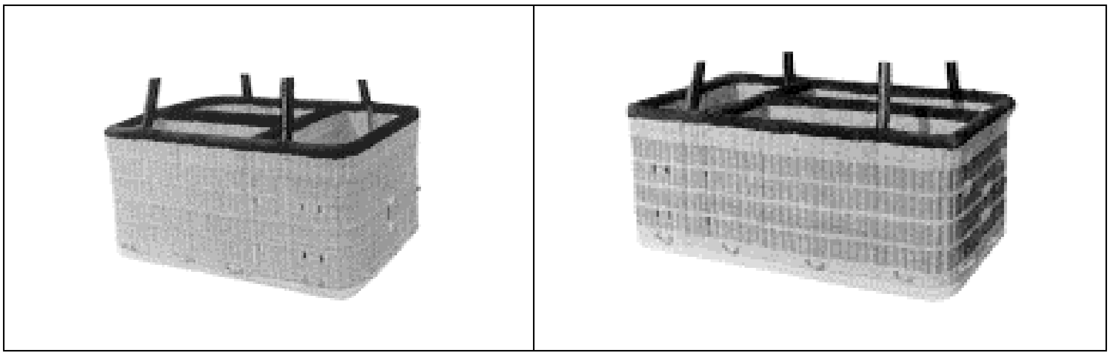


Figure 4 Single T-partitioned baskets. The pilot and the fuel cylinders are in the small compartment separated from the passengers.

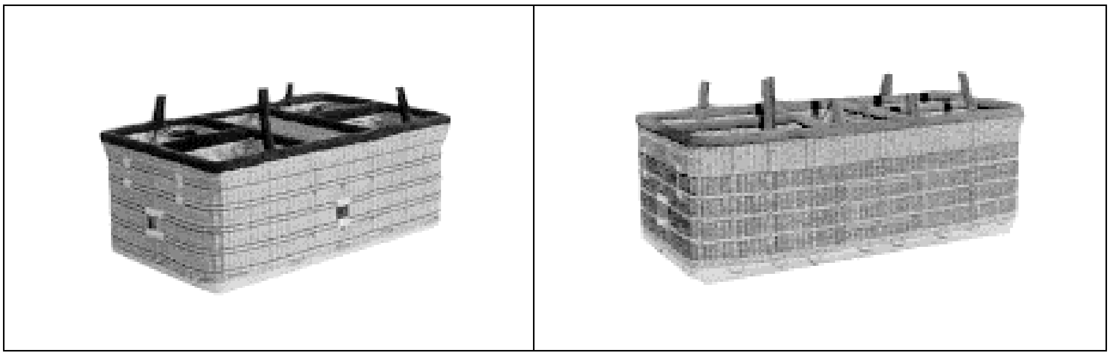


Figure 5 Double T-partitioned baskets. The pilot and the cylinders are in the middle compartment separated from the passengers.

The balloon baskets described in Appendix A, Table 1 were divided into the following types: open, single partition, mini-T partition, single T-partition and double T-partition. These types are illustrated in Figures 1 to 5. The number of occurrences and the types of injuries for each type of basket are given in Table 2. The basket types in Table 2 are ranked according to the number of serious injuries counted in the databases.

The basket type in which the highest number of serious injuries was sustained is the open basket. The basket type in which the lowest number of serious injuries was sustained is the single partitioned basket. 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 baskets nor the number of flights are registered in a national database, and no other information source was available. According to the balloon operators that are involved in this project 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 might be the safest basket. Agreeing with the number of serious injuries, the balloon operators involved in this project think the open basket is the least safe basket. They think that the chance of injuries is higher in an open basket, because this basket type has no protection against contact with the fuel cylinders and other passengers.

Table 2 Basket types ranked according to number of serious injuries sustained.

Basket type	Number of occurrences	Type of injuries	Injury severity
Open	10	1 broken leg 4 broken ankle 1 broken arm 1 broken rib 1 serious back injury 2 serious injuries* 1 bruising shoulder 6 minor injuries*	10 serious 8 minor
Mini T-partition	5	1 fractured pelvis 3 broken arm 1 broken rib 1 broken bone in foot 1 shoulder ligament injury 4 bruises and grazes	6 serious 4 minor
Single T-partition	6	1 broken leg (2 broken legs of 1 passenger counted as 1) 1 broken tibia 1 broken ankle 1 broken arm 1 serious injury* 1 sprained ankle 1 minor knee injury 1 cut hand and bang to head	5 serious 3 minor
Double T-partition	5	1 broken leg 1 broken tibia 1 serious injury* 4 sprained ankles 1 minor knee injury 1 minor back injuries 12 minor injury*	3 serious 18 minor
Single partition	2	1 broken leg 1 broken ankle 4 minor injuries*	2 serious 4 minor
Unknown	2	1 broken ankle 1 broken lower leg	2 serious

*) Not specified in the UK databases.

The types of injuries sustained by passengers ranked according to injury risk are given in Table 3. At least 54% of the serious injuries were fractures of the lower extremities (at least, because not specified serious injuries were counted as other serious injury).

Table 3 Passenger injuries sustained during landings ranked according to injury risk.

Type of injury	Number of occurrences
Broken leg (upper or lower)	7 (2 broken legs of 1 passenger counted as 1)
Broken ankle	7
Sprained ankle	5
Broken arm	5
Bruises and grazes	4
Broken rib	2
Minor knee injury	2
Serious back injury	1
Minor back injuries	1
Shoulder ligament injury	1
Bruising shoulder	1
Fractured pelvis	1
Broken bone in foot	1
Cut hand and bang to head	1
Serious injuries*	3
Minor injuries*	22

*) Not specified in the UK databases.

Only in 12 accidents in the UK databases was it stated that instructions about the landing positions were given, and only in 6 cases parts of the instructions that were given were described. Therefore, the information about the passenger landing positions from the databases was too poor to make a relationship with the risk of injury.

Comparing the literature findings with the UK database findings the following can be concluded:

- The UK databases comply with the literature findings about the main cause of the hot-air balloon accidents (landing), the main cause of the serious injuries (collision with ground) and the most common serious injury (fractured lower extremity).

3 Opinions of Balloon Operators

3.1 Questionnaires to Balloon Operators

With the agreement of the CAA, TNO sent an e-mail to balloon operators from 6 large UK Ballooning companies with a request to provide the following information:

1 Landing positions instructed to their passengers.

2 a) Number of flights per year from 1998 to 2002.

  b) Number of flights per year in which any injury was sustained by any passenger during the landing from 1998 to 2002.

  c) Number of minor, serious and fatal injuries sustained by a passenger during the landing from 1998 to 2002 (injury type according to the definition of the International Civil Aviation Organization (ICAO), Annex 13, see Section 2.1)

  d) Most common injury sustained by passengers during landings from 1998 to 2002.

3 a) Most common landing scenarios according to their opinion.

b) Typical landing scenarios in which injuries are most likely to occur.

The answers on the instructed landing positions varied much in detail. Therefore, a list with the various instruction items was sent to the balloon operators and they were asked whether they use it or not. Also, the instructions on the landing positions are dependent on the type and size of the basket. Therefore, the balloon operators were also asked to provide the following:

4 Types of baskets (partitioned, size etc.) that their company uses for passenger flights.

The landing instructions of the 6 UK balloon operators and the number of balloon operators that use them are given in Table 4. All questioned balloon operators instructed their passengers to stow loose objects away and ensure no part of the body protruded over the basket rim. The three different landing positions mentioned by the different balloon operators ranked according to occurrence are (times mentioned between brackets):

- Back to travel direction and lean with back against partition or basket side, knees slightly bent. (3)
- Seating on foam cushion with backs in direction of travel against partition or basket side, knees slightly bent and head against basket rim. (2)
- Shoulder into direction of travel and lean with shoulder against front partition or basket side, shoulder width and feet pointing in direction of pilot in the middle of the basket, and knees slightly bent. (1, plus 1 only in small non-partitioned baskets)

The number of flights the balloon companies made between 1998 and 2002 varied from 381 to 752. The average number of flights each year was approximately 100. In total only 3 minor injuries were recorded in the period from 1998 to 2002. One was a neck injury (whiplash), and two were sprained knees. The sprained knees appeared to be sustained by passengers who were not following the landing instructions.

Table 4 Instruction items given by 6 UK balloon operators.

Landing position	Number of balloon operators
Backs to travel direction and lean with back against partition or basket side.	5
Shoulder into direction of travel and lean with shoulder against front partition or basket side.	1
Lean with head against padded rim of basket/partition.	3
Head may not protrude the basket rim	4
Head must protrude the basket rim	2
Holding onto ropes in front	5
Holding onto 1 rope in rear and 1 in front	1
Knees slightly bent	4
Seating on foam cushion	2
Distance between ones feet	2
Heavy/large people in front of non-partitioned basket, smallest at the back	3
Stow loose articles away	6

The balloon operators mentioned that the landing scenario depends on the wind speed, wind changes, space to land, sort of ground (e.g. clay, chalk, etc.), the undulation of the land, and pilot skill. However, the most common landing scenario, which is also the most convenient for the passengers, they described was:

- Low speed and low approach: wind speed <8 knots, vertical landing speed <200 feet/min., a short drag (<10 metres).

Five balloon operators mentioned the basket to finish upright at this landing scenario and one mentioned to finish with the basket gently tipping over on its side.

Other common landing scenarios described were:

- Low speed and high approach: wind speed <8 knots, vertical landing speed <200 feet/min., a short drag (<10 metres) with the basket remaining upright.
- High speed and low approach: wind speed >8 knots, vertical landing speed <200 feet/min., long drag (>10 metres) with the basket remaining upright.
- High speed and low approach: wind speed >8 knots, vertical landing speed <200 feet/min., long drag (>10 metres) with the basket tipping over.
- High speed and high approach: wind speed >8 knots, vertical landing speed up to 500 feet/min., long drag (>10 metres) with the basket tipping over.

Landing scenarios in which injuries are most likely to occur according to the balloon operators are:

- Fast landing (wind speed >10 knots) with a small area to land (high approach) which results in a heavy landing. (6)
- Fast landing resulting in a long (bouncing) drag. (2)
- Fast landing with the basket tipping over at touch down. (1)
- Fast landing with the basket contacting obstacles (e.g. tree stumps) during the drag. (1)
- Rapid changes of wind speed or direction causing the basket to turn by which a basket corner or the left- or right-side edge digs into the ground. (1)

The basket types used by the 6 questioned balloon operators are given in Table 5. The number of passengers that are carried by the various baskets types and sizes used by the balloon operators varied from 3 to 20 adults including the pilot. From the questionnaires no relation could be found between the basket types used by the balloon operators and the landing positions they instruct to their passengers. Also no relation could be made between basket types used by the balloon operators and the number of injuries sustained, since in total only 3 minor injuries were recorded.

Table 5 Basket types used by the 6 questioned UK balloon companies.

Basket types	**Number of balloon companies**
Open	3
Single partition	1
Mini T-partition	0
Single T-partition	2
Double T-partition	5

3.2 Interviews with Balloon Operators

TNO visited the Bristol Balloon Fiesta 2003 to gather more information on passenger landing positions, especially for the baskets that are modelled in this study. During the visit, more evidence was gained about the instructions on the landing positions, depending on the type and size of the basket that a balloon operator uses. However, all pilots instructed the passengers to have their knees slightly bent and keep a small distance between the feet. The most common instructed passenger positions for the baskets that are modelled are described below.

In the open basket there are usually four cylinders. In the open basket the passengers hold onto the cylinders and/or the rope handles where they can hold on most tightly. In the open basket there is not enough space for all four passengers to be in the backward position. Therefore, two passengers are at the front of the basket in a sideways position back to back between the cylinders. The other two passengers are at the back side by side between the cylinders with their backs in travel direction. In the backward position the four cylinders are each situated in a corner. In this report this configuration of the passenger positions in the open basket will still be referred to as 'backward position'. Section 3, Figure 3 shows the passengers in an open basket in the backward position. In the open basket in the sideways position all four passengers are at the front with their left arm/shoulder against the front side. In the sideways position the cylinders are all four at the back side of the basket. Section 3, Figure 4 shows the passengers in an open basket in the sideways position.

In the double T-partitioned basket there are usually four cylinders, which are situated in the middle compartment with the pilot so the passengers cannot get into contact with the cylinders. In the double T-partitioned basket there are two passengers in each compartment. In the backward position the passengers hold onto the rope handles in front of them. The front passengers lean with their backs against the basket front side and the back passengers against the partition in travel direction. Section 3, Figure 5 shows the passengers in a double T-partitioned basket in the backward position. In the sideways position the passengers hold onto the rope handles sideways from them. 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 passengers at the outer left and right side of the basket also lean with their backs against the outer left and right basket sides, respectively. Section 3, Figure 6 shows the passengers in a double T-partitioned basket in the sideways position.

4 Definitions for Simulations

4.1 Landing Scenarios

The landing scenario with the highest risk of injury is, both according to the UK databases and to the 6 questioned balloon operators, the heavy landing. The four other dangerous landing scenarios described by the balloon operators were in the first five landing scenarios with the highest risk of injury resulting from the UK databases. From these five landing scenarios, four landing scenarios are numerically simulated. The definitions of these landing scenarios, agreed by all the parties involved in this study, are given in Table 6.

Table 6 Definitions of the landing scenarios that are simulated.

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

4.2 Basket Types

The open basket is thought to be the most dangerous basket type, and the double T-partitioned basket is thought to be the safest basket type. Therefore, it was agreed by all the parties to model these two basket types. The open basket model should be of a common type that can carry four passengers, one pilot and four cylinders. The double T-partitioned basket model should be of a common type that can carry two passengers in each partition (eight passengers in total), two pilots and four cylinders. The space for four passengers in the open basket should be approximately the same as for four passengers in the double T-partitioned basket in order to be able to evaluate the effect of partitions on the injury risk. A total of four human models, modelling the passengers, are put inside each basket model with space left at the right side of the basket for the pilot. In the double T-partitioned basket the human models are on the left side of the basket only. Rope handles are modelled at positions in the baskets as provided by the manufacturer.

4.3 Landing Positions

The backward as well as the sideways passenger landing positions are simulated in both the open and double T-partitioned basket. The pilot is not modelled, since to investigate the safety of the pilot was not the aim of this study, and thereby, it will make the simulations too complicated. The details of the backward and sideways passenger positions in both the open and double T-partitioned basket, as agreed by the CAA, are given in Table 7.

Table 7 Definitions of passenger landing positions that are simulated.

Landing position	Open basket	Double T-partitioned basket
Backward	• 2 front passengers lean with arm/shouder against basket front side, back to back • 2 back passengers are side by side with their backs in travel direction • knees slightly bent • hold onto cylinders and/or rope handles • small distance between feet • cylinder in each corner	• 2 front passengers lean with back against basket front side • 2 back passengers lean with back against basket partition • knees slightly bent • hold onto rope handles both in front of passenger • small distance between feet • cylinders separated from passengers
Sideways	• 4 front passengers lean with left shoulder against basket front side • knees slightly bent • hold onto cylinders and/or rope handles • small distance between feet • four cylinders at the basket back side	• 2 front passengers lean with shoulder against basket front side facing in pilot direction • 2 back passengers lean with shoulder against basket partition facing in pilot direction • knees slightly bent • hold onto rope handles sideways from passenger • small distance between feet • cylinders separated from passengers

5 Real-life Landing Experiments

To get an indication of the accelerations and deformations of the basket during the landings, real-life landing experiments were performed (in The Netherlands). For the experiments a 4-person round-top open basket was used, see Figure 7. With this basket the pilot could best control the landing speed. Three acceleration load cells were placed in three perpendicular directions fixed to the basket ground-plate at the front of the bottom plate (landing side), see Figure 6. The amplifier and the data recorder were placed in the basket in a way that they were protected against impacts, see Figure 6. In order to relate the acceleration measurement to the landing scenario, digital videos of the landings were made. Thereby, large targets (used in car crash tests) were put on each corner and in the middle of each side of the basket to get an idea of the deformation of the basket during the landing, see Figure 7. The pilot tried to imitate three different landing scenarios: heavy landing, drag landing and landing with a corner against a ditch wall.

Figure 6 Measuring equipment in the basket.

Figure 7 Basket with which the real-life landing tests were performed.

The maximum horizontal landing speed was 4.1 knots, and the maximum vertical landing speed was 560 ft/min. 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. Due to the low wind speed the measured horizontal basket speeds in the experiments were, however, lower than the ones that are prescribed to the basket model. Still, the acceleration curves gained from the experiments can be used to get a feeling for the acceleration magnitude. The measured accelerations of all the landings are shown in Appendix B.

From the movies it could be seen that there was hardly any deformation of the basket frame during the impact on the ground. The only deformation of the basket that could be seen was the wall moving outwards at the place the passenger leaned during the impact on the ground.

The pilot obviously tried not to bring the passengers nor himself into danger. However, during the heavy landings of 500 ft/min. and 560 ft/min. the man (middle-aged) who performed the acceleration measurements injured his ankle. He was sitting on one heel at that time. His ankle had recovered a month later. This means that there is a risk of injury at a downward acceleration of 120 m/s^2. Afterwards, the authors learnt that bending too far through the knees during a balloon landing can hurt the ankles, lasting a few seconds, at vertical landing speeds over 400 ft/min.

6 Material Parameters

To the best knowledge of the authors and the parties involved in this project the material properties of woven wicker are unknown. Therefore, the stiffness of wood was chosen for the basket stiffness, which is 12 GPa. The Young's Modulus of the rope handles was defined to be equal to that of hemp, which is 32 GPa. The soil stress-strain characteristic was defined to be approximately the same as that of a soccer field. This soil characteristic was determined from another TNO project.

Section 3 Evaluation of Current Passenger Landing Positions

1 Numerical Models

1.1 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). MADYMO is a combined multi-body (MB) and finite element (FE) software package. 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. In this human model various detailed segments can be included, see Figure 1. The detailed segments provide more detailed information, and some can simulate muscle activity.

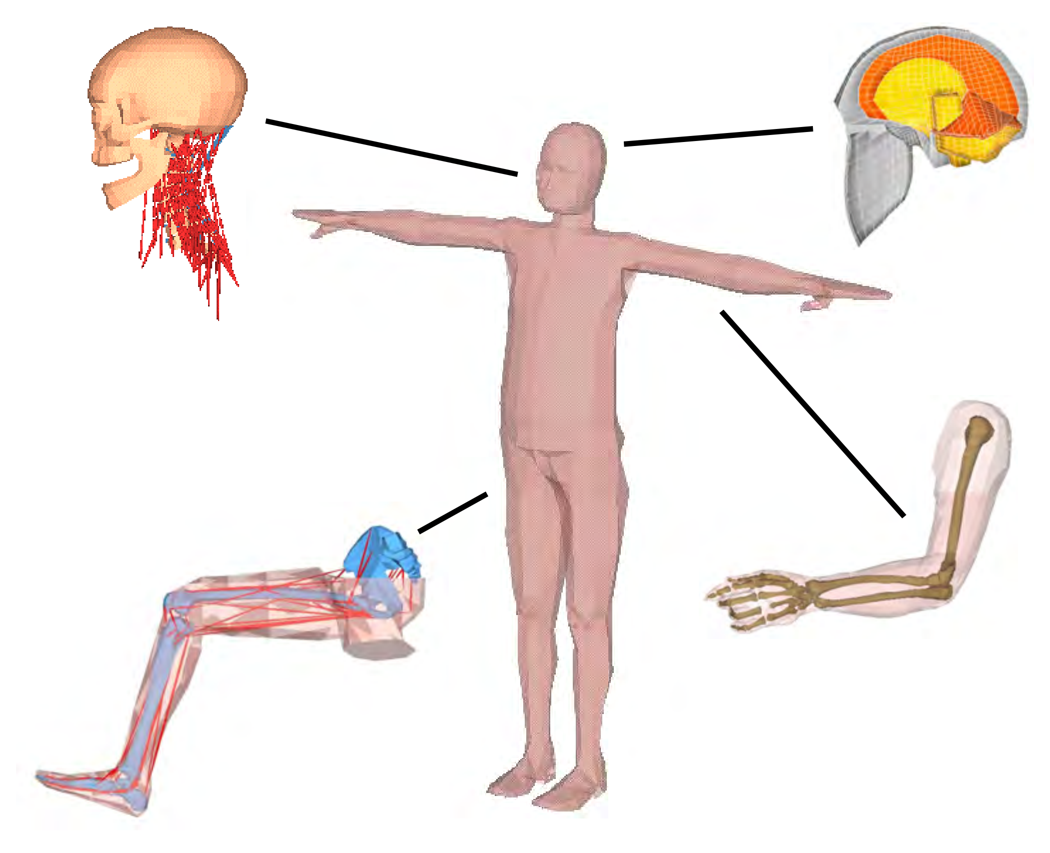


Figure 1 Average male multi-body human model with detailed segment models.

Since leg injuries are most common in balloon accidents, two detailed legs were included in the human model for this study, see Figure 2. 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.

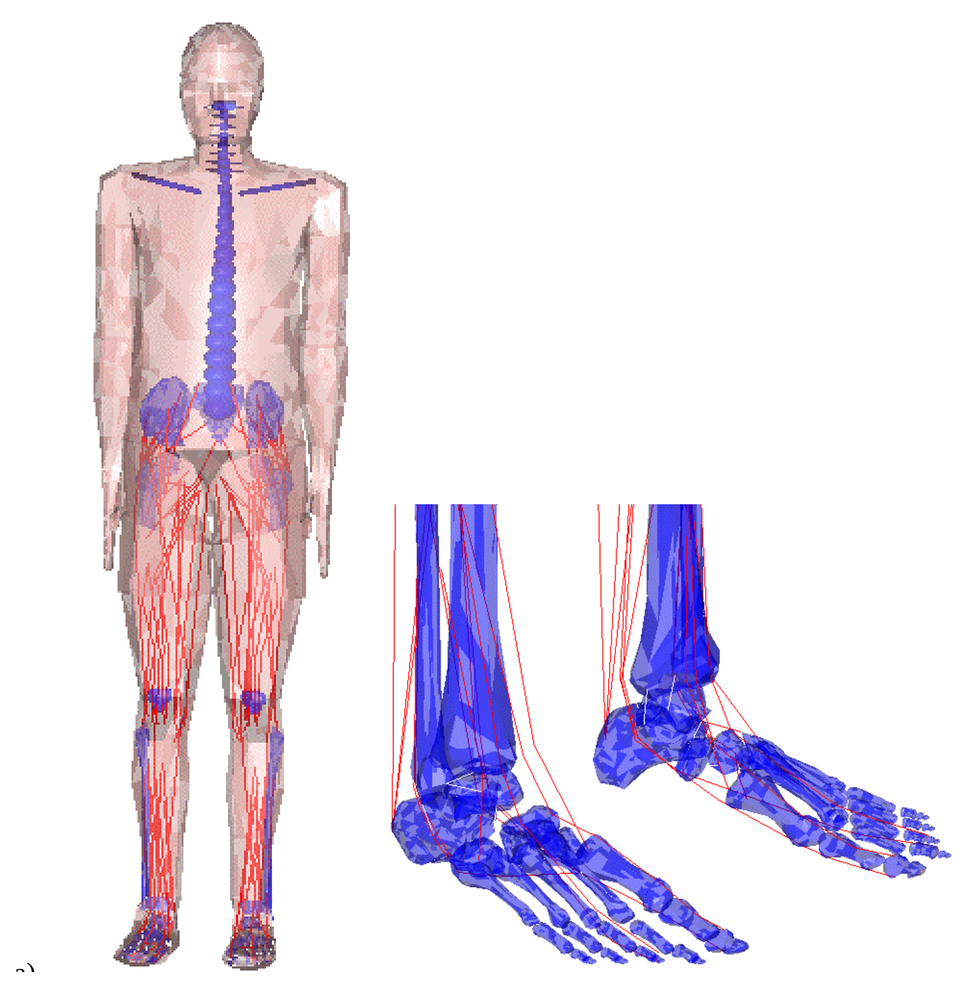


Figure 2 Left: MADYMO multi-body model with detailed legs left.
Right: close up of the bones, ligaments and muscles in the feet.

1.2 Basket Model

The geometries and masses of the baskets, including the top frame padding, and cylinders were provided by Lindstrand Ltd. The basket sizes and weights are given in Table 1.

Table 1 Basket types and properties that were modelled.

Basket Type	Size [m]	Empty Weight [kg]	No People	No Cylinders
Open	1,22 X 1,62	88	4 passengers, 1 pilot	4
Double T	1,48 X 2,56	230	8 passengers, 2 pilot	4

The basket as well as the cylinder geometries were converted to a rigid FE MADYMO model. The basket handles were each modelled by two tension-only elements. The basket handles were positioned at basket according to the drawings of Lindstrand Ltd. The open basket model was provided with four cylinders, each with a full weight of 48 kg. The cylinders are rigidly connected to the basket. In the double T-partitioned basket the cylinders are separated from the passengers, therefore no cylinders were put in the double T-partitioned basket model in order to save calculation time. However, the weight of the four cylinders in the double T-partitioned basket was included in the basket model. The two basket models with the positions of the cylinders for the backward and sideways landing positions are shown in Figure 3 to Figure 6.

1.3 Positioning of Human Models

The human models were positioned in the baskets 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 placed with their feet 1 cm above the basket bottom plate and 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 basket 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 used as initial conditions in the landing simulations. The initial backward and sideways landing positions of the human models in the open and double T-partitioned basket model are shown in Figure 3 to Figure 6. The weight and inertia of the pilots and the four passengers that were not represented by human models was compensated for by modelling bodies, each with the weight and inertia of a human model, fixed to the appropriate position in the baskets.

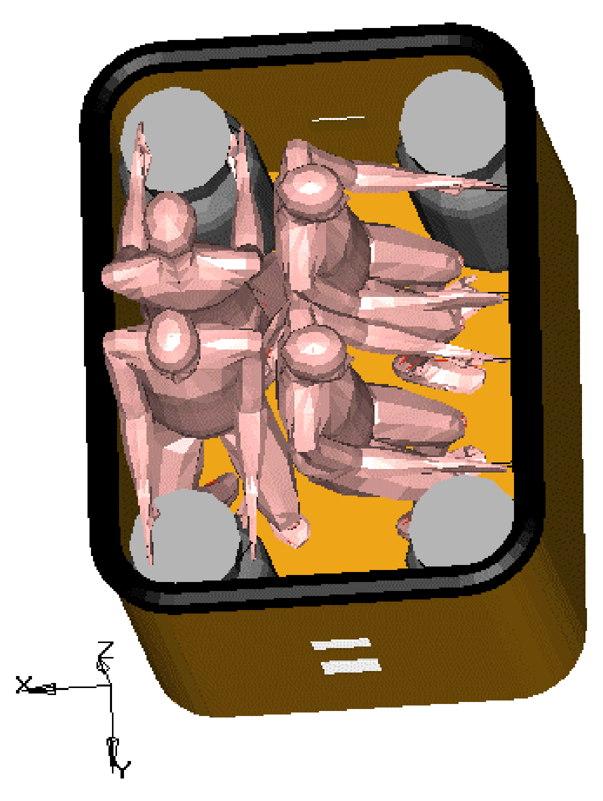


Figure 3 Model of open basket with four passengers in the backward position.

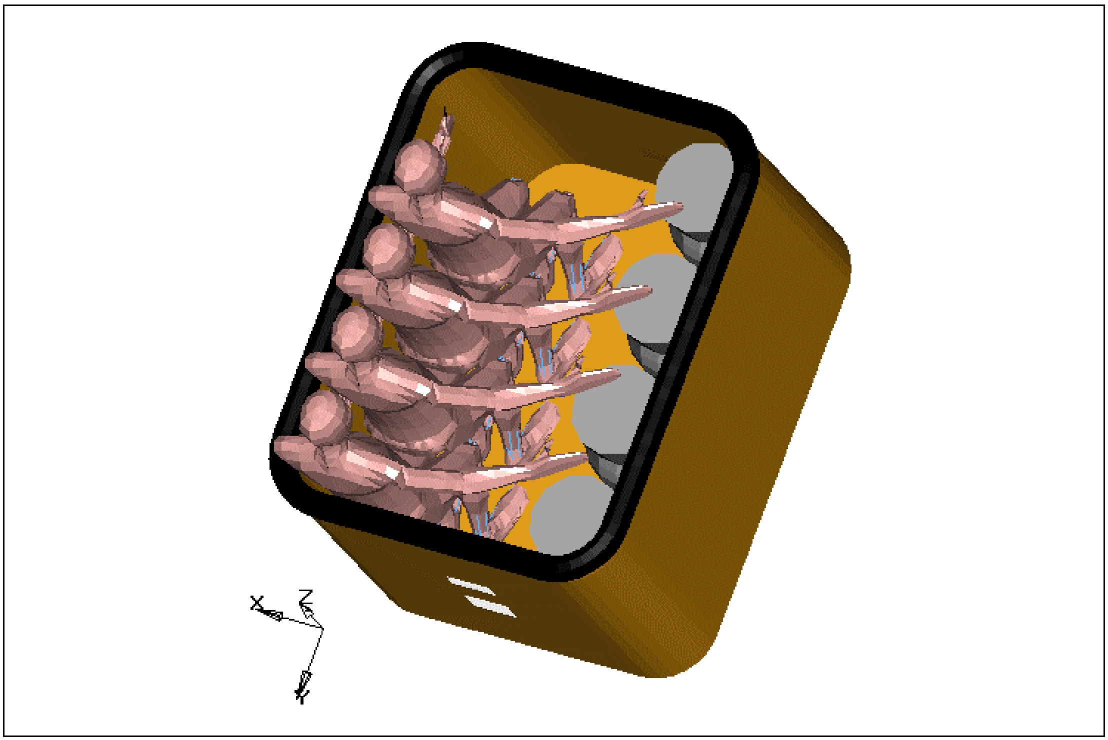


Figure 4 Model of open basket with four passengers in the sideways position.

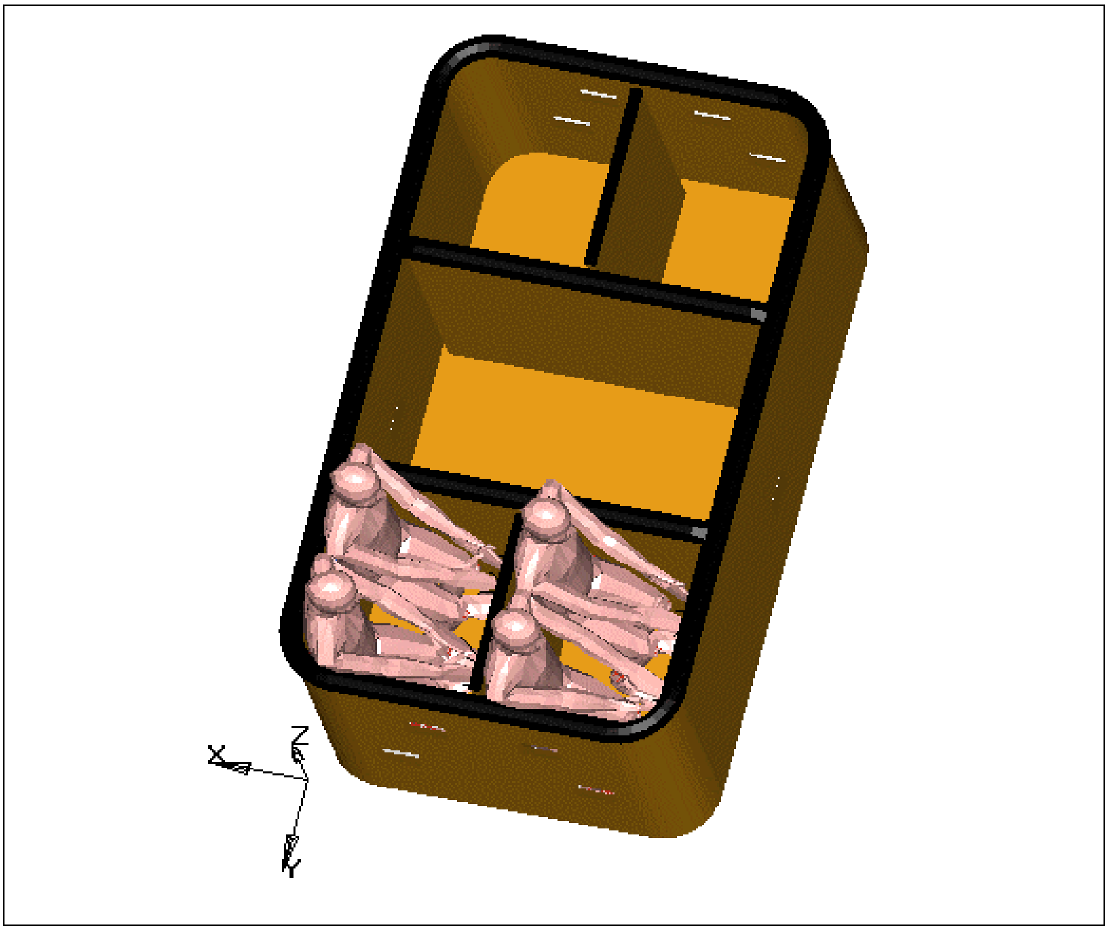


Figure 5 Model of double T-partitioned basket with four passengers in the backward position.

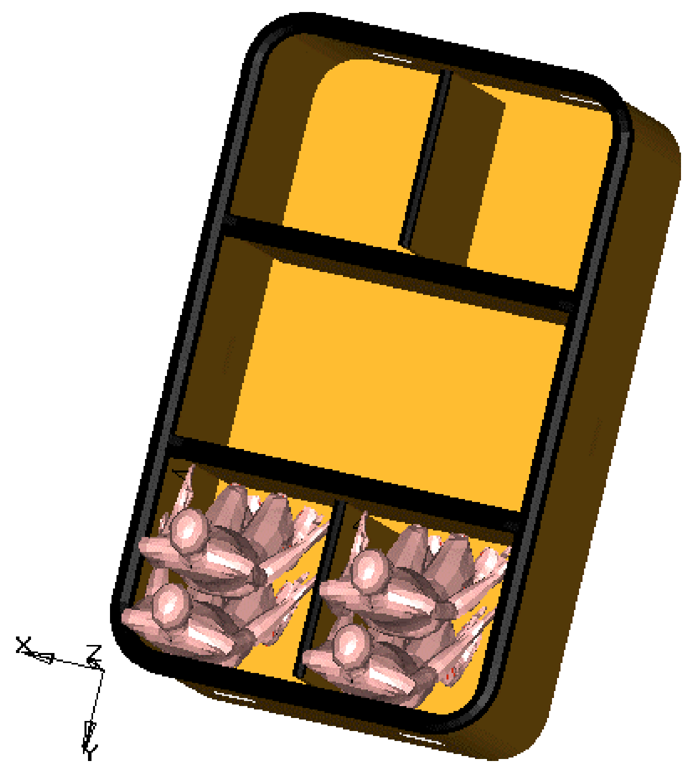


Figure 6 Model of double T-partitioned basket with four human models in the sideways position.

1.4 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 initial landing position under gravity. The human models stayed in their initial position during the whole simulation. This confirms that the leg muscle activity applied is realistic for an initial hot-air balloon landing position. The muscle activities that were activated and their activity levels that were prescribed in the landing simulations are given in Table 2. An activity level of 1 indicates that the muscle generates its maximum force. All other leg muscles in the human model were not activated. Anatomical pictures of the leg muscles are shown in Figure 7 and Figure 8.

Table 2 Activated leg muscles and activity levels.

Leg muscles	**Activity level [-]***
Gluteus maximus	0.10
Ilio psoas	0.15
Rectus femoris	0.25
Vastus	0.30
Gastronemius	0.10
Soleus	0.15
Tibialis anterior	0.40

*) An activity level of 0 indicates no muscle activity, and an activity level of 1 indicates maximum muscle activity.

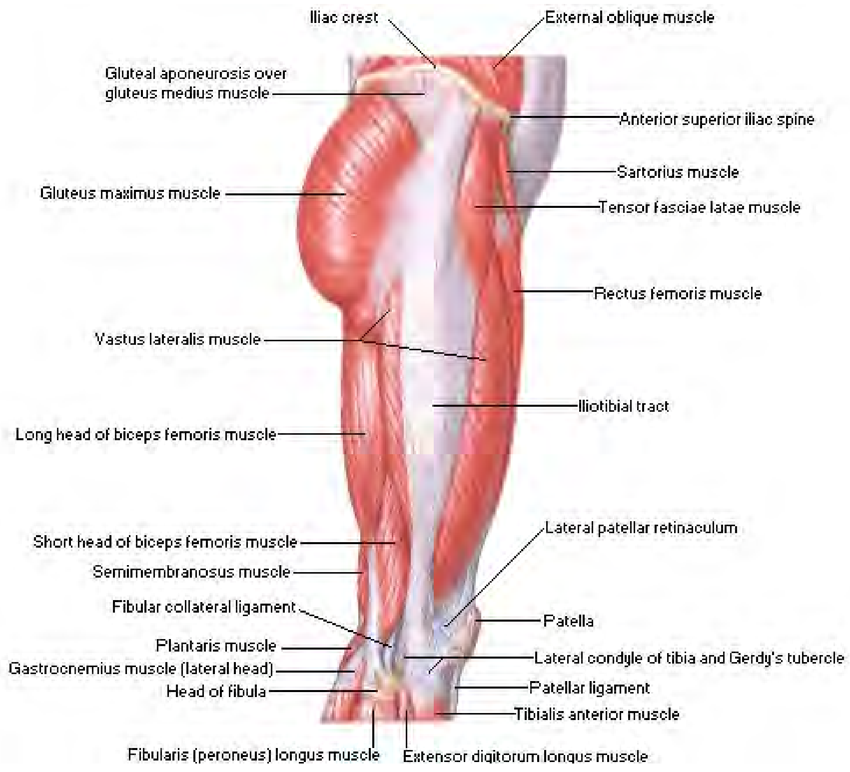


Figure 7 Muscles of the upper leg.

Figure 8 Muscles of the lower leg.

1.5 Boundary Conditions

The four different landing scenarios were simulated by prescribing initial forward and downward velocities to the basket, cylinders, the pilot and the passengers according to the definitions in Section 2, Table 6. 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. The basket was assumed to be rigid with respect to the ground and to the human models. In the 'contact to obstacle' and 'contact to obstacle at corner' landing simulations a bar (simulating a low stone wall) was defined with which the basket made contact before contacting the ground. The bar was assumed to be rigid with respect to the basket. The 'heavy', 'contact to obstacle' and 'contact to obstacle at corner' landings were simulated for 200 ms each. The 'tip-over' landing was simulated for 1000 ms. The contact with the ground and/or the obstacle resulted in an acceleration of the basket.

The resulting basket accelerations were validated by comparing the basket accelerations of two test simulations to the measured accelerations in the landing experiments. The validation of the x-acceleration (forward) was performed by simulating landing test 5 (see Appendix B) with the open basket. The prescribed initial velocities of the simulation of test 5 were 2 knots forward and 560 ft/min. downward. The measured and calculated x-accelerations are shown in Figure 9. The validation of the y- and z-acceleration (lateral and downward) was performed by simulating landing test 6 (see Appendix B), also with the open basket. The prescribed initial velocities in the simulation of test 6 were 4 knots forward and 500 ft/min. downward. The measured and calculated y- and z-accelerations are shown in Figure 10 and Figure 11, respectively. From Figure 9 to Figure 11, it can be seen that the calculated accelerations were consistent with the measured accelerations in the landing experiments.

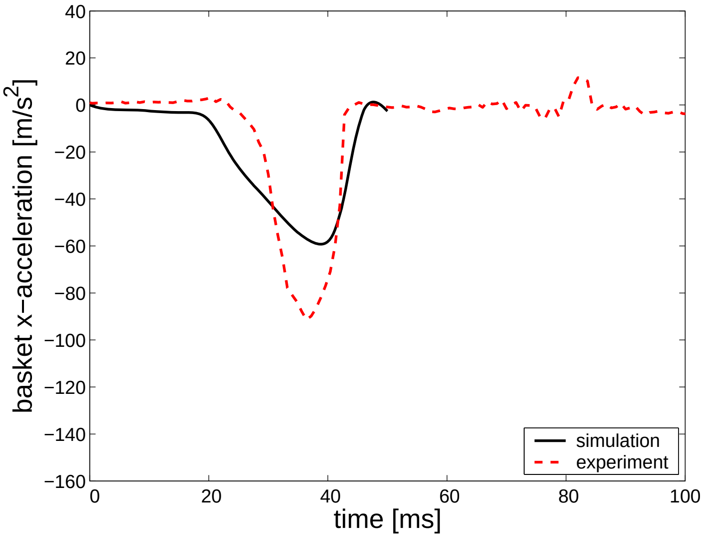


Figure 9 Basket x-acceleration measured in the landing tests and calculated in the simulation.

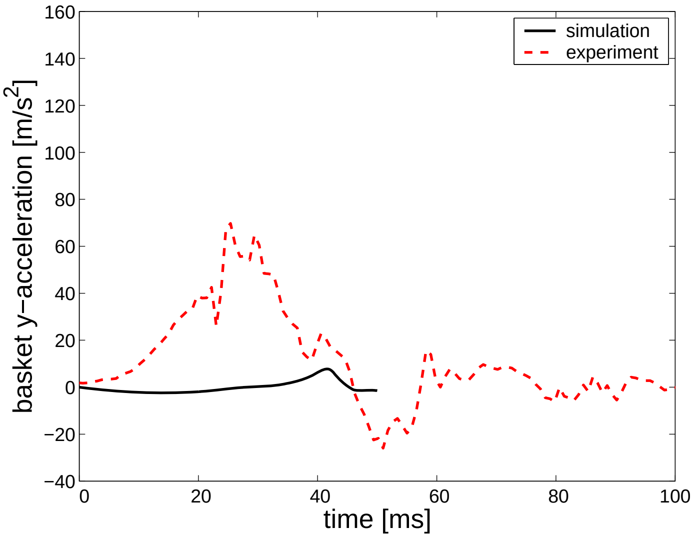


Figure 10 Basket y-acceleration measured in the landing tests and calculated in the simulation.

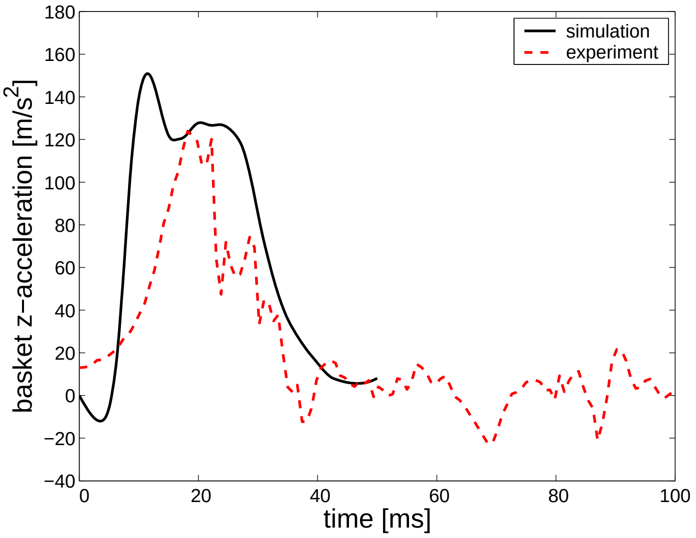


Figure 11 Basket z-acceleration measured in the landing tests and calculated in the simulation.

1.6 **Injury Criteria**

For the evaluation of the safety of the landing positions the injury values from the simulation output are compared. The injury criteria that were chosen are based on the passenger injuries (see Section 2, Table 3) and the movements that are most common in balloon landings.

The injury criterion that is used to evaluate the chance of a femur fracture is the transverse femur bending moment. The tolerance limit for the transverse femur bending moment according to literature is 320 Nm (Kress *et al.* 1993). The injury criterion that is used to evaluate the chance of a broken tibia is the tibia compression force. The tolerance limit for the lower tibia compression force according to literature is 7.8 kN (Begeman & Prasad 1990). The injury criterion that is used to evaluate the chance of a broken ankle is the lower tibia dorsiflexion (toe to tibia rotation) torque. The tolerance limit for the lower tibia dorsiflexion torque according to literature is 60

Nm (Portier *et al.* 1997). The injury criteria that is used to evaluate the chance of a sprained ankle are the strains on the anterior talofibular, the posterior talofibular and the calcaneofibular ligament. An anatomical picture of the foot ligaments is shown in Figure.12. Injuries due to a twist of the ankle are mostly related to one of these three ankle ligaments (Attarian *et al.* 1985, Siegler *et al.* 1990). The rupture strain of all the ligaments in the leg model was set to 50 % (Attarian *et al.* 1985, Nigg 1990, Parenteau 1996).

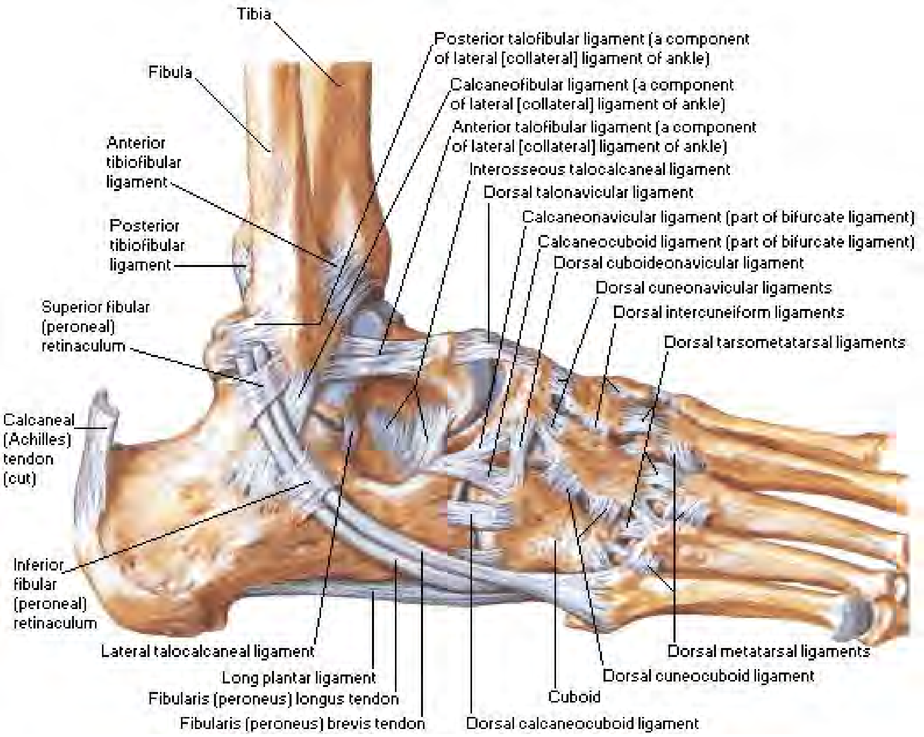


Figure 12 Ligaments of the foot.

The injury criteria that are used to evaluate the chance of head injury (concussion) are the resultant head angular acceleration and the resultant head linear acceleration. The injury tolerance limit for the resultant head angular acceleration is 1800 rad/s^2 (Ommaya *et al.* 1967). The injury tolerance limit for the resultant head linear acceleration is approximately 1000 m/s^2 taking into account the duration of the acceleration (Versace 1971). An overview of the injury criteria and values that are used to evaluate the chance of injuries to the legs and to the head are given in Table 3.

Table 3 Injury criteria and tolerance limits used to evaluate the safety of the passenger landing positions.

Injury	**Injury Criterion**	**Tolerance Limit**
Femur fracture	transverse femur bending moment	320 Nm
Tibia fracture	lower tibia compression force	7.8 kN
Ankle fracture	lower tibia dorsiflexion torque	60 Nm
Ankle sprain	anterior talofibular ligament strain	50 %
	posterior talofibular ligament strain	50 %
	calcaneofibular ligament strain	50 %
Head injury	resultant head angular acceleration	1800 rad/s^2
	resultant head linear acceleration	1000 m/s^2

2 Simulation Results

In order to compare the worst case passenger injuries of each simulation the maximum injury criteria values were calculated. Figures 1 to 8 in Appendix C show all the maximum injury criteria values resulting from all the simulations. The black horizontal line in the bar diagrams show the injury tolerance limits given in Table 3. Since there were several unknown parameters concerning the basket, the injury criteria values cannot be interpreted as an indication for injury directly. However, at the landing velocities that were simulated (see Section 2, Table 6) injuries are likely to occur according to the accident database (see Appendix A). Thereby, the calculated maximum injury criteria values are around the injury tolerance levels. This indicates that the loading conditions on the human models are not far from the real loading conditions at these landing velocities.

Although the chance of injuries cannot be calculated from these simulations, the simulation results of the different landing positions can be compared to each other. For an easy comparison of the different landing positions a relative value for the injury risk was calculated for each kind of injury given in Table 3 (femur fracture, tibia fracture, ankle fracture, ankle sprain and concussion) for each simulation. For this, the maximum injury criteria values 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. The relative injury value for a sprained ankle was defined as the mean of the relative maximum injury criteria values for the strain of the anterior talofibular ligament, posterior talofibular ligament and calcaneofibular ligament (see Table 3). The relative injury value for a concussion was defined as the mean of the relative maximum injury criteria values for head angular acceleration and head linear acceleration (see Table 3). The relative injury values for each kind of injury for all the simulations are shown in Figure 13 to Figure 17.

It must be noted that the relative values for the injury risks can only be compared qualitatively and not quantitatively. 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

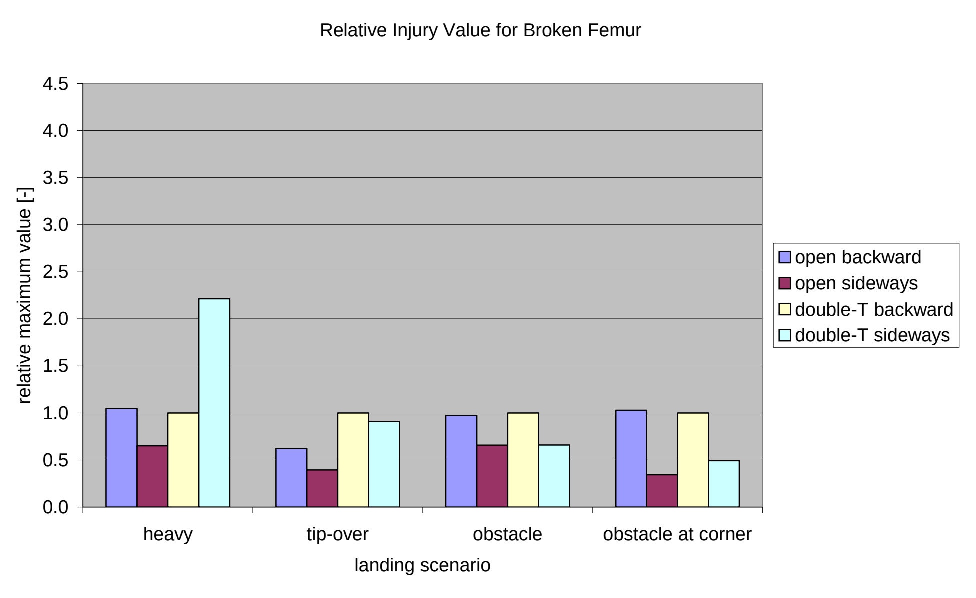


Figure 13 Relative maximum transverse femur bending moment resulting from the simulations.

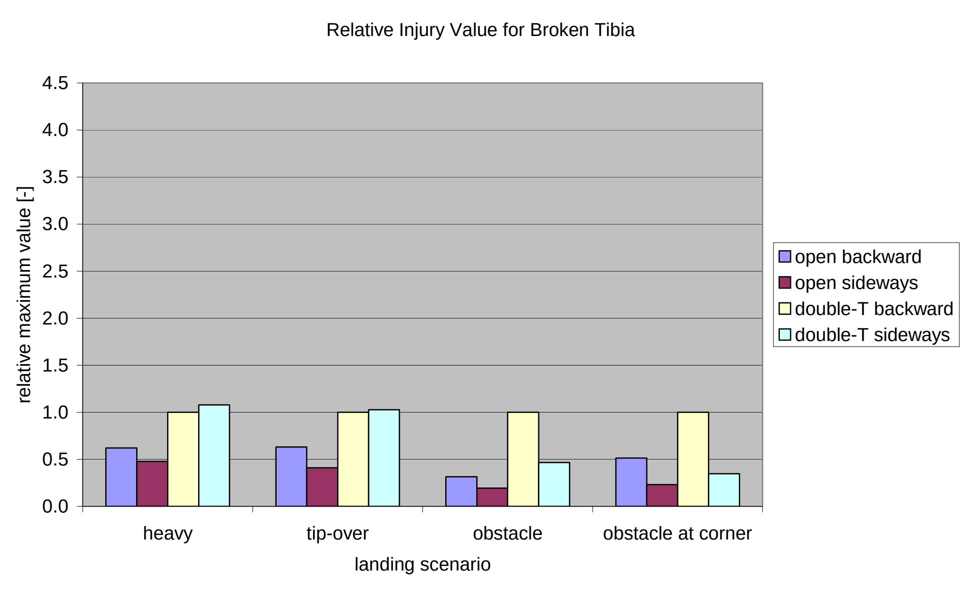


Figure 14 Relative maximum lower tibia compression force resulting from the simulations.

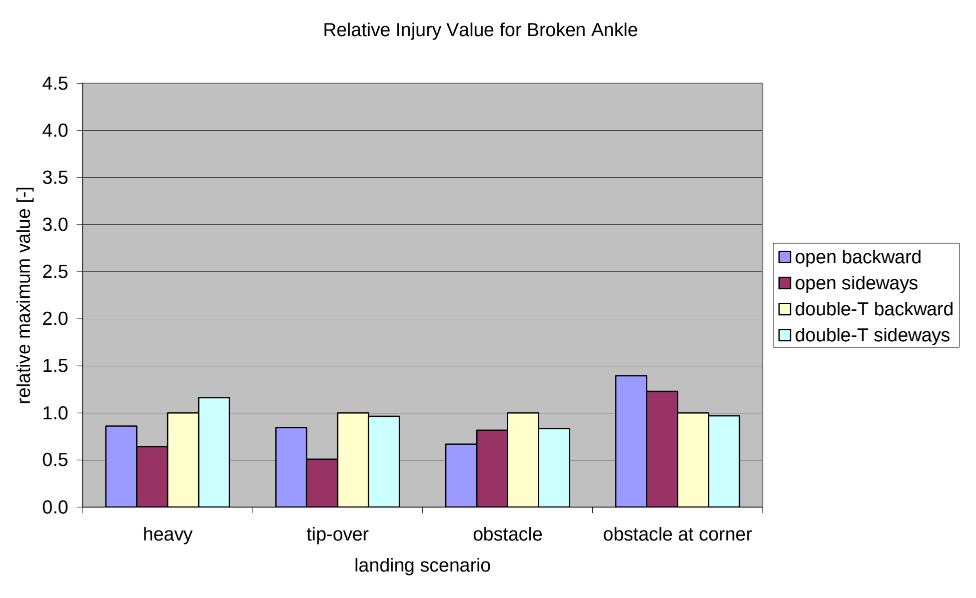


Figure 15 Relative maximum lower tibia dorsiflexion torque resulting from the simulations.

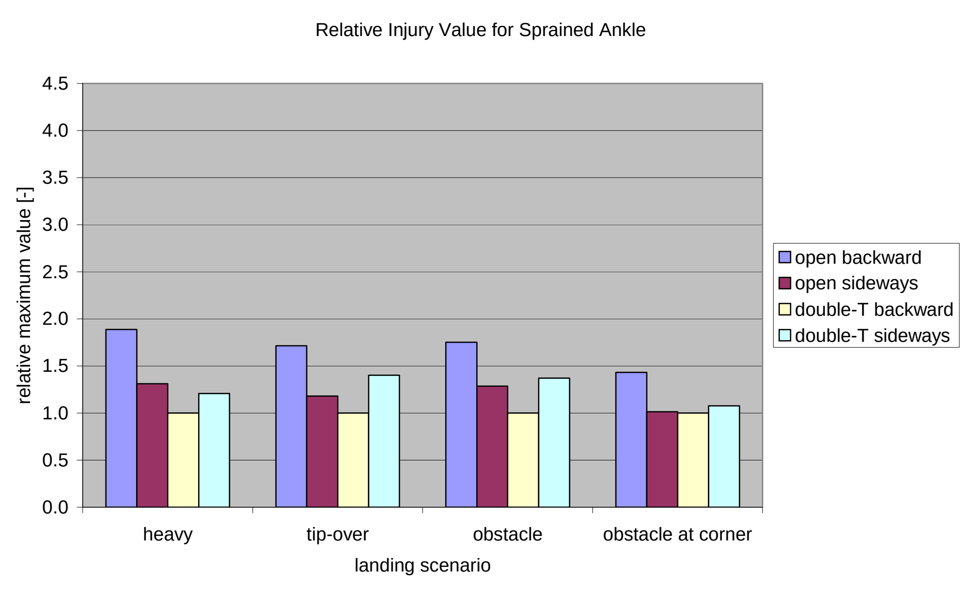


Figure 16 Relative maximum of anterior talofibular ligament, posterior talofibular ligament and calcaneofibular ligament strain resulting from the simulations.

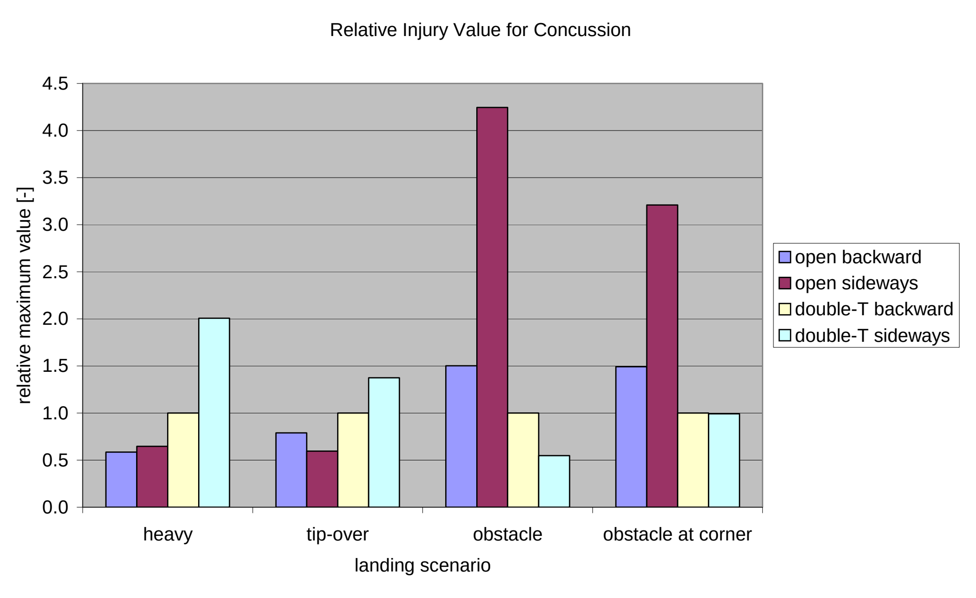


Figure 17 Relative maximum of the resultant head angular and linear accelerations resulting from the simulations.

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. Thus, each kind of injury was counted for the same amount in the relative value for the total of injuries. Figure 18 shows the relative value for the total of injuries for all the simulations.

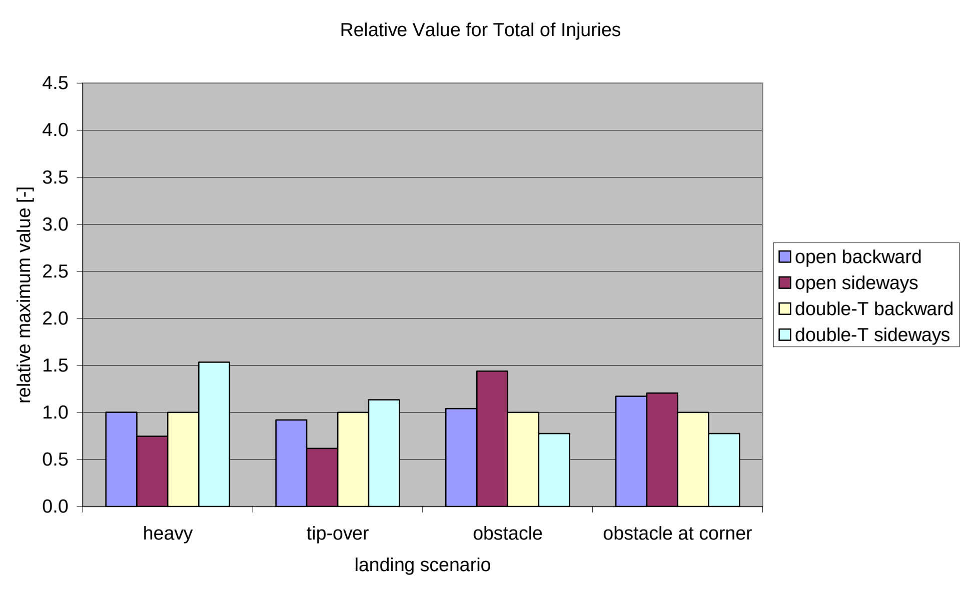


Figure 18 Relative maximum value for the total of injuries resulting from the simulations.

3 Discussion

From Figure 18 it seems that for the open basket the sideways landing position is safer than the backward position in the heavy and tip-over landing, and the backward position is safer when an obstacle is hit. An explanation for the sideways position seeming to be safer in an open basket in the heavy and tip-over landing was found in the movies of the simulations. In the movies it could be seen that contact between the human models after the impact on the ground was seen more in the backwards landing position than in the sideways landing position. This resulted in higher injury values for broken femur, broken ankle and sprained ankle for the back passengers in backward position than for the passengers in sideways position, see Figure 13, Figure 15 and Figure 16. The reason for the higher injury risk when an obstacle is hit is caused by the more than two times higher relative injury value for concussion in the sideways position than in the backwards landing position, see Figure 17. Almost all other relative injury values are lower for the sideways position than for the backward position in the open basket when an obstacle (at corner) is hit.

From Figure 18 it seems that for the double T-partitioned basket the backwards landing position is safer than the sideways position in the heavy and tip-over landing, and the sideways position is safer when an obstacle is hit. This is mainly caused by all the lower relative injury values for the legs for the backward position than for the sideways position in the heavy and tip-over landing, see Figure 13 to Figure 16. The reason for the higher injury risk when an obstacle is hit is caused by the about twice as high relative injury values for a broken femur, broken tibia and concussion for the backward position than for the sideways position, see Figure 13, Figure 14 and Figure 17. This can be explained by the difference in the positions of the feet for the sideways and backward position. The movies of the simulations showed that the basket rotates forwards after the impact on the ground in the heavy and even more in the tip-over landing causing a higher upward acceleration at the back of the basket than at the front. When an obstacle is hit the basket starts to rotate around the position where it hit the obstacle which causes an even larger upward acceleration at the back of the basket than in the tip-over landing. In the backward position the feet are farther away from the basket rotation point than in the sideways position which explains the higher relative injury values for a broken femur and broken tibia for the backward position. The rotation of the basket caused that the relative injury values for the front passengers were almost all lower than for the back passengers for both landing positions in all landing scenarios simulated. The twice as high relative injury value for concussion can be explained by the head contacting the rim in case of the backward position and not in the sideways position when the basket hits an obstacle at the front side.

The relative injury value for concussion were in most of the simulations higher for the back passengers than for the front passengers. And, for the double T-partitioned basket the relative injury values for a broken femur, tibia and ankle were in all cases higher for the back passengers. Both can be explained by the fact that the basket rotated forwards after the impact on the ground causing a higher upwards acceleration for the back passengers than for the front passengers. In the double T-partitioned basket the relative injury values for a broken femur, tibia and ankle were in all cases higher for the back passengers than for the front passengers. However, for the open basket in the backwards landing position the relative injury values of the femur, tibia and ankle were not in all cases higher for the back passengers than for the front passengers. This can be explained by the fact that the back passengers hit the front passengers on their femurs that affect the relative injury values for a broken femur, tibia and ankle of the front passengers.

Figure 18 does not show a significant difference between the safety of the open basket and the double T-partitioned basket. This is possibly due to the fact that the open basket modelled in this study has some advantages as well as disadvantages with respect to the double T-partitioned basket. An advantage of the open basket is that the passengers each have more space than in the double T-partitioned basket. A disadvantage of the open basket is that there are four passengers with four cylinders in one space between which contact can take place, and in the double T-partitioned basket are only two passengers in one space. Although, in the open basket in the sideways position, the passengers do not get into contact with the cylinders due to the favourable position of the cylinders at the back side of the basket. Another disadvantage of the open basket is that it is lighter than the double T-partitioned basket resulting in higher accelerations at impact on the ground at the same landing speed.

From the four landing scenarios that are simulated, the landing scenario in which the basket hits an obstacle over the whole frontal side of the basket (obstacle landing) seems to be the most dangerous, see Appendix C.

It must be noted that in the simulations the hands of all passengers always stay fixed to the handles. If one or more passengers, especially in the back of the open basket, let the handles loose, this would increase the injury risk for the front passengers.

In order to get more confidence in the calculated injury values, a parameter variation on all the simulations was performed. The leg muscle activity level was the parameter that was varied, since the muscle activity level is an unknown parameter and for this study it is interesting to see the effect of muscle stress on the injury criteria values. The leg muscle activity level was increased by 50% for all the muscles that were activated, see Table 2. The results of the simulations are shown in Appendix D. The results of the parameter variation simulations show that the higher leg muscle activity level changed the relative value for the total of injuries by more than 25% in two cases (compare Figure 19 to Figure 18):

- The relative value for the total of injuries for the sideways position in the double T-partitioned basket in the heavy landing; and
- that of the sideways position in the open basket in the obstacle at the corner landing.

However, the safest landing positions found for the original simulations coincide with that found for the parameter variation simulations. This indicates that the simulation results can be used to evaluate the safest passenger landing positions..

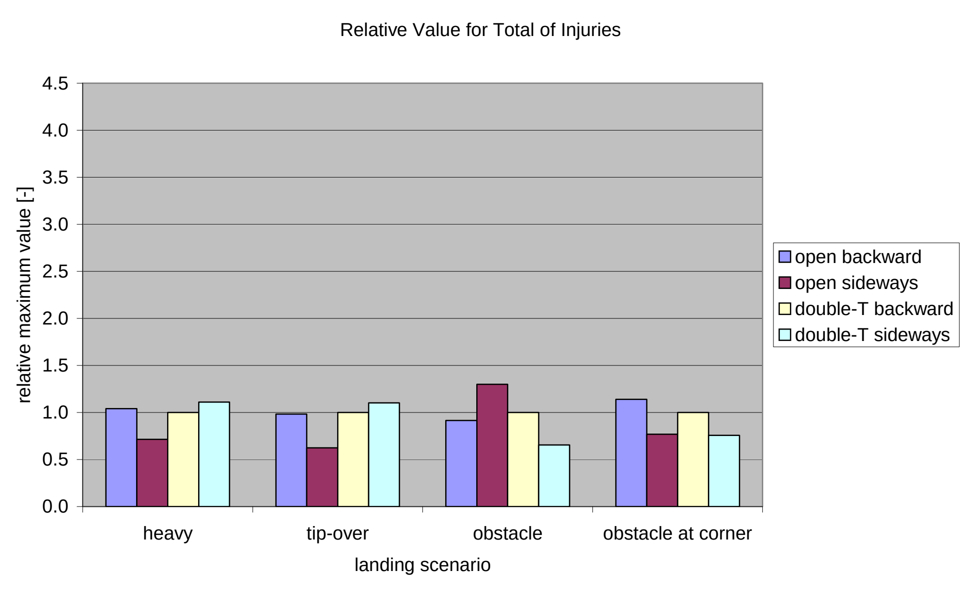


Figure 19 Relative maximum value for the total of injuries resulting from the parameter variation simulations.

4 Conclusions

From the simulation results the following can be concluded about the safety of the landing positions in the open and double T-partitioned basket:

- In the open basket the sideways landing position is safer than the backward position in the heavy and tip-over landing, except for the head when an obstacle is hit during the landing.
- In the double T-partitioned basket the backwards landing position is safer than the sideways position in the heavy and tip-over landing, but less safe when an obstacle is hit during the landing.
- Since the heavy and tip-over landing are more common than a landing during which an obstacle is hit, the sideways position may be adopted as the overall safest landing position in the open basket and backward position as the overall safest landing position in a double T-partitioned basket.
- The passengers in the front compartments of the double T-partitioned basket seem to be safer than in the back compartments in all landing scenarios simulated.

Section 4 Evaluation of Current Protection Strategies

1 Numerical Models

For the evaluation of the protection strategies, basically the same numerical models (human models and basket models) were used as for the evaluation of the current landing positions (see Section 3.1). To model the protection strategy the positions of the human models and/or the basket models were adapted. The protection strategies were simulated for the sideways landing position in the open basket and the backwards landing position in the double T-partitioned basket.

2 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. None of the protection strategies had been subjected to scientific scrutiny. However, the balloon operators believe that the protection strategies that they apply themselves reduce the chances of injuries. Together with the CAA, the UK balloon operators and the UK ballooning companies that were involved in this study, decided to evaluate the following protection strategies:

- Skids under the basket: Skids decrease the friction between the ground and the basket during the landing, which decreases the landing deceleration in horizontal direction. Skids also have a damping effect in vertical direction due to the skids digging into the ground. Moreover, reducing the horizontal deceleration decreases the chances of a tip-over landing.
- Foam padding in the basket: Foam padding on the floor reduces the impact under the feet during the landing. Foam padding at the inner sides reduces the impact on the back and shoulders. Foam passing on the rim reduces the impact on the back, shoulders and head.
- Two different passenger landing positions:
    - Knees more bent: The passengers have their knees more bent during the landing such that their neck is in the rim padding which reduces the head accelerations.
    - A foam block for the passengers to sit on during the landing decreases the impact load under the feet.

3 Skids under the Basket

Skids under the basket were modelled by simply reducing the friction factor between the basket and the ground. The friction factor was reduced from 0.35 to 0.15. The digging of the skids into the ground was not modelled, since this is more complicated and there were no data. 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 effects of skids on the relative injury values for the heavy landing are shown in Figure 1 to Figure 5. The effect of the skids on the relative value for the total of injuries for the heavy landing is shown in Figure 6. The bar diagrams show that the effect of the skids on the relative injury values was less than 25%, which can be considered as not significant given the effect of increased leg muscle activity (see Section 3 paragraph 3). However, the real change of the landing deceleration and basket rotation caused by skids is not known. To study the real effects of skids on the basket movement, experimental testing is needed.

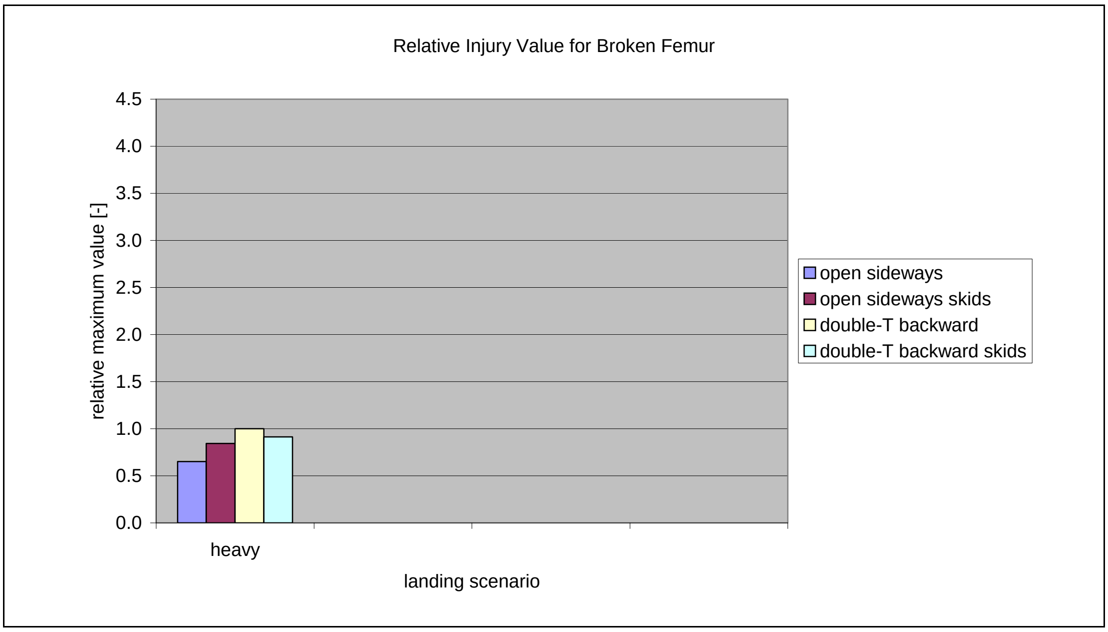


Figure 1 Relative maximum transverse femur bending moment resulting from the original simulations and the simulations with skids modelled.

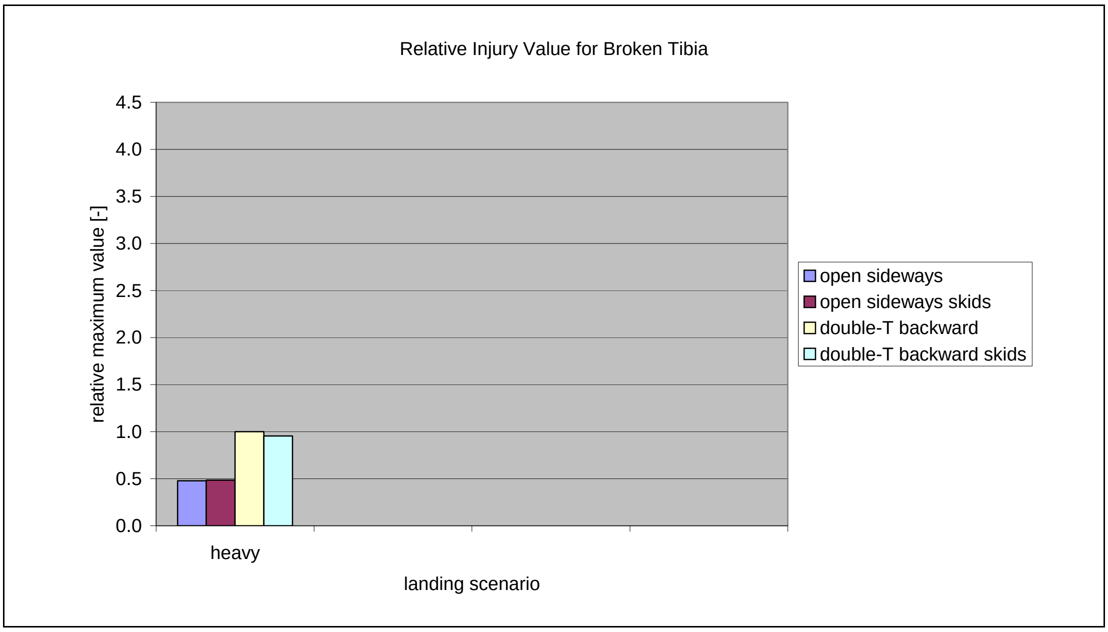


Figure 2 Relative maximum lower tibia compression force resulting from the original simulations and the simulations with skids modelled.

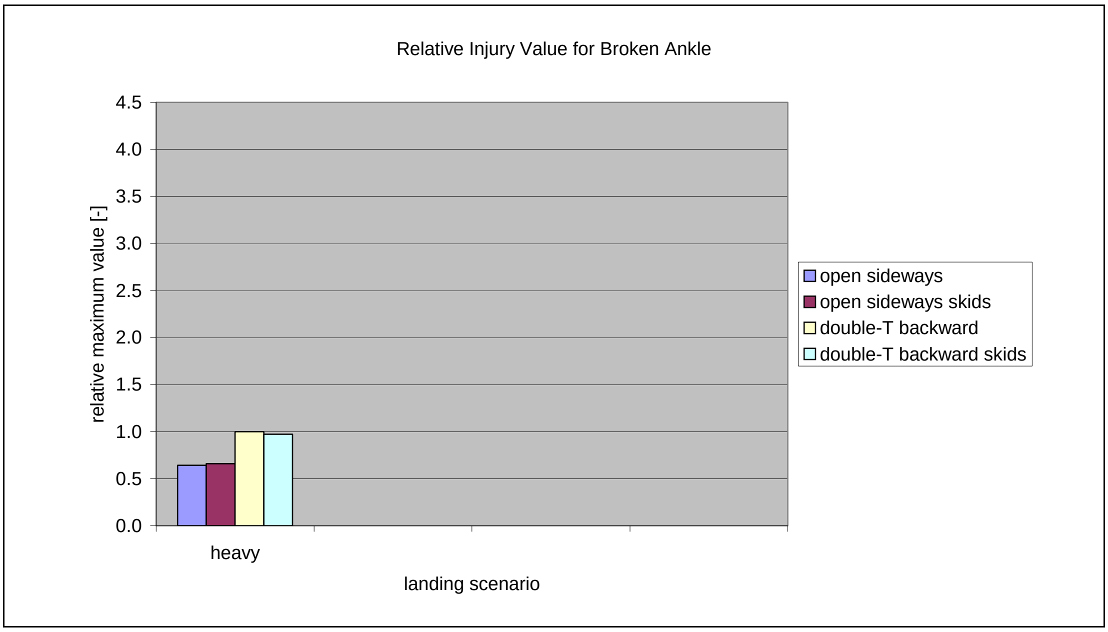


Figure 3 Relative maximum lower tibia dorsiflexion torque resulting from the original simulations and the simulations with skids modelled.

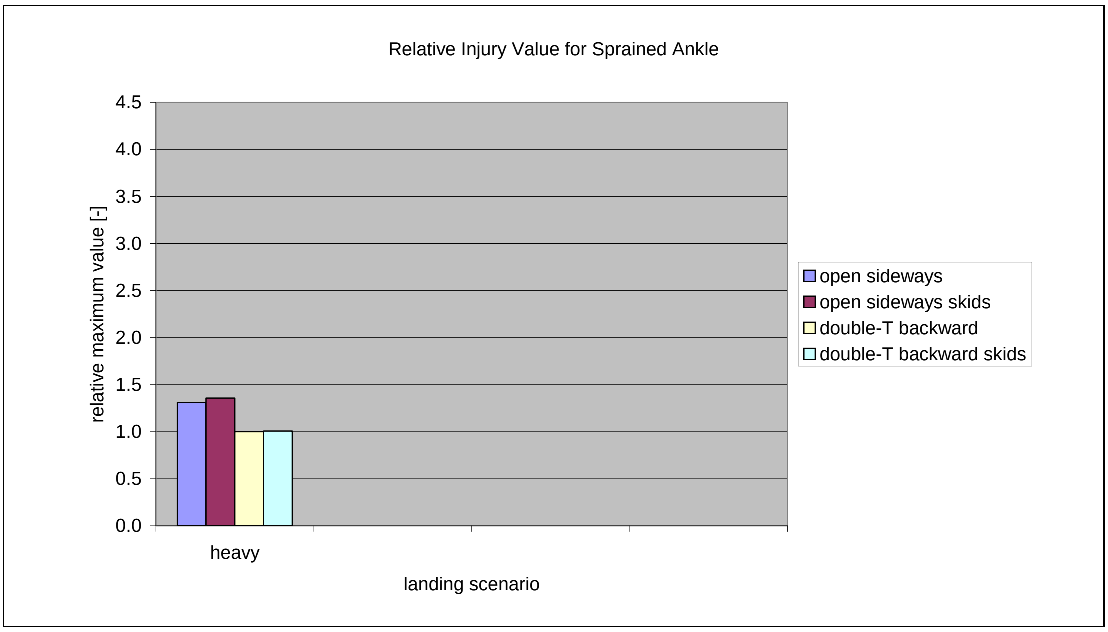


Figure 4 Relative maximum of anterior talofibular ligament, posterior talofibular ligament and calcaneofibular ligament strain resulting from the original simulations and the simulations with skids modelled.

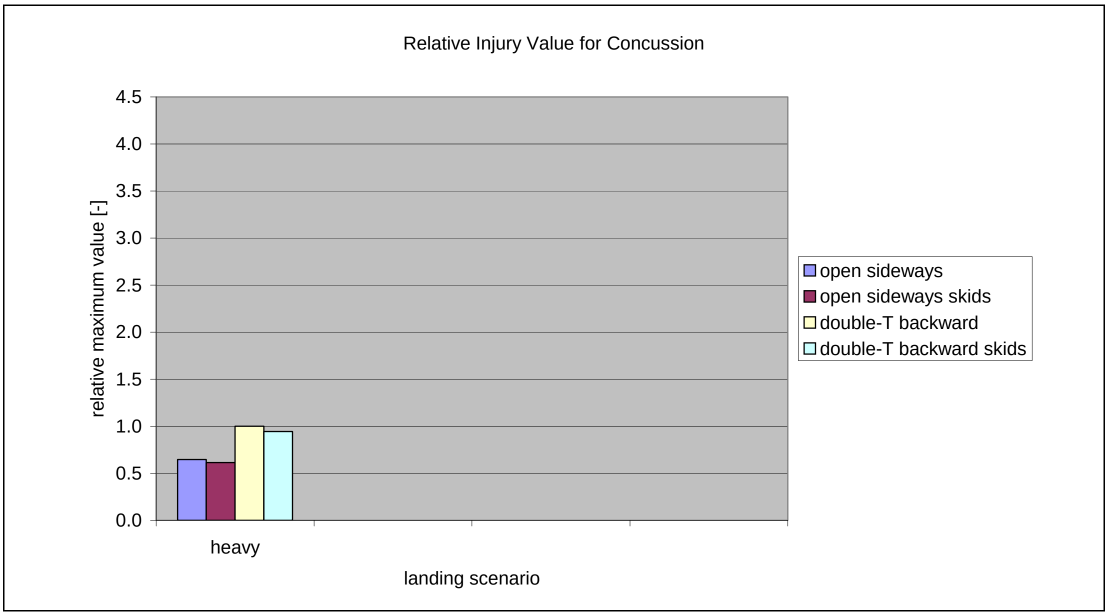


Figure 5 Relative maximum of the resultant head angular and linear accelerations resulting from the original simulations and the simulations with skids modelled.

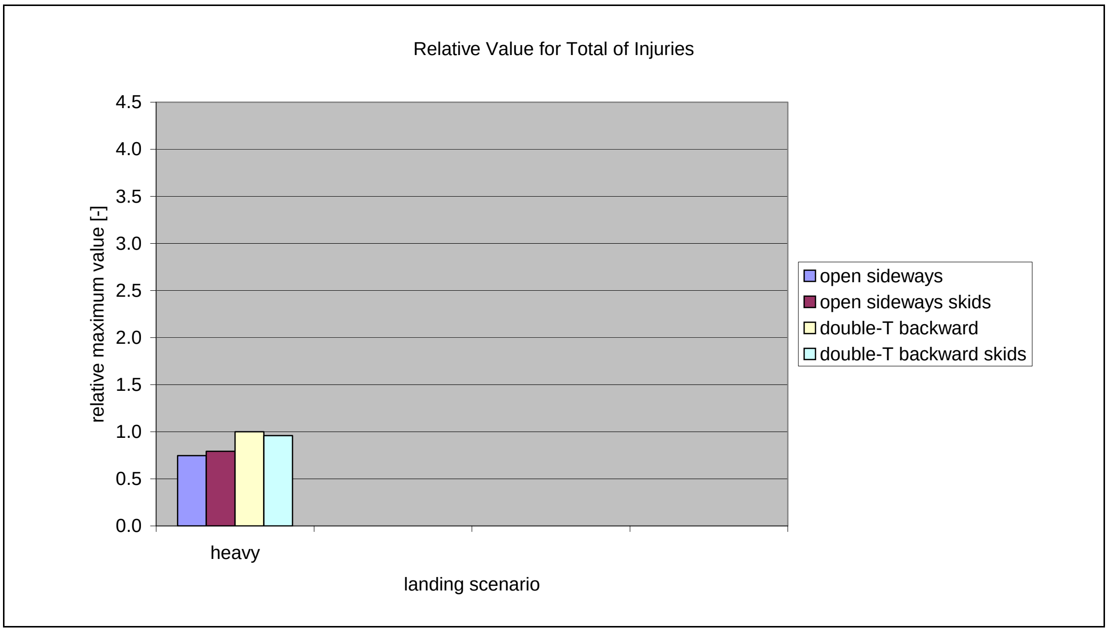


Figure 6 Relative maximum injury value for the total of injuries resulting from the original simulations and the simulations with skids modelled.

4 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., see Table 1. For the foam type of the rim padding no material specifications could be obtained from the manufacturer, therefore the foam type of the inner sides padding was adopted. 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. In reality, the foam padding applied to the basket floor and the inner sides are covered by a cordura fabric to protect the foam against wear and tear. The foam applied to the basket rim is covered by leather for the same purpose. The foam coverings were not modelled, since they are very thin, and therefore will have a negligible effect on the relative injury values.

Table 1 Specifications of the basket foam padding.

Applied to	Thickness [mm]	Foam Type
Floor	34	K430[1]
Inner sides	9	K424[1]
Rim	50	K424[1,2]

1. Manufactured by Keeling Rubber & Plastics Ltd.
2. No material specifications could be obtained from the manufacturer, therefore foam type K424 was adopted for the basket model.

The effects of the foam padding on the relative injury values for all the landing scenarios are shown in Figure 7 to Figure 11. The effect of the foam padding on the relative value for the total of injuries for all the landing scenarios is shown in Figure 12. Figure 12 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 relative injury 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% when an obstacle is hit at the front side and by more than 30% when an obstacle is hit at the corner. 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, the relative value for the total of injuries was even slightly increased. The increase of the relative value for the total of injuries for the open basket in sideways position was mainly caused by the increased relative injury value for a broken femur. The reason for this is that the human models can penetrate the basket sides, floor and rim more in the case where foam padding is modelled than without, causing the human models to be in a slightly different position and resulting in slightly different results than in the original simulations. However, in reality the penetrations of the passengers in the foam padding will have a negligible effect on the passenger positions before the peak impact. For the open basket the foam padding decreased the relative injury values for broken tibia and broken ankle by more than 25% for all landing scenarios.

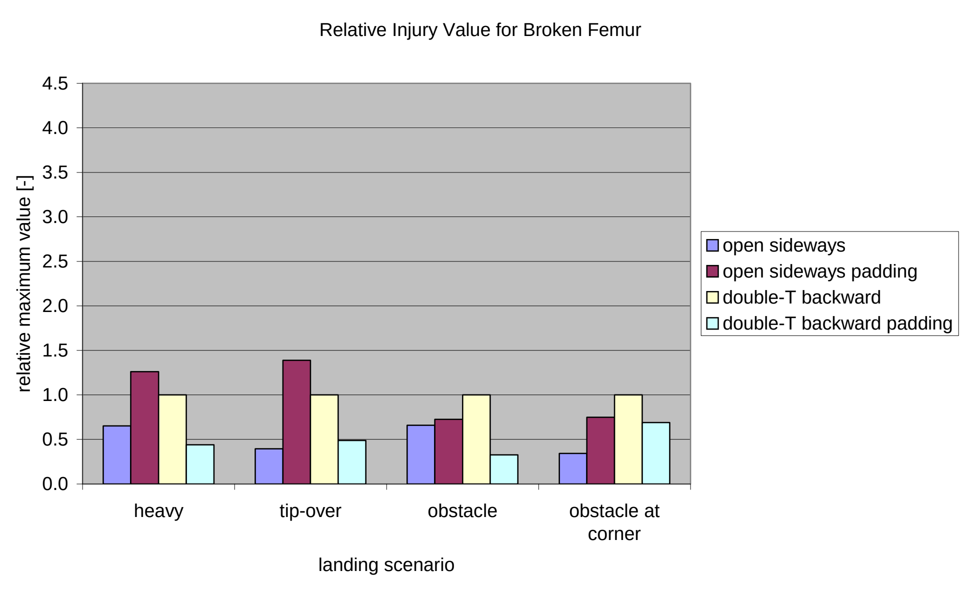


Figure 7 Relative maximum transverse femur bending moment resulting from the original simulations and the simulations with foam padding modelled.

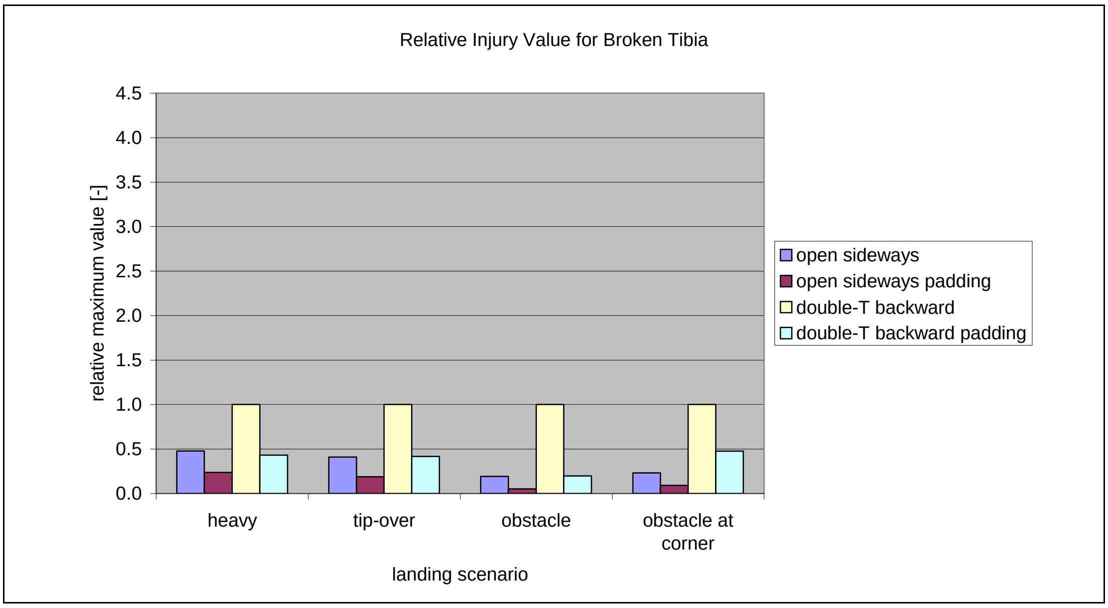


Figure 8 Relative maximum lower tibia compression force resulting from the original simulations and the simulations with foam padding modelled.

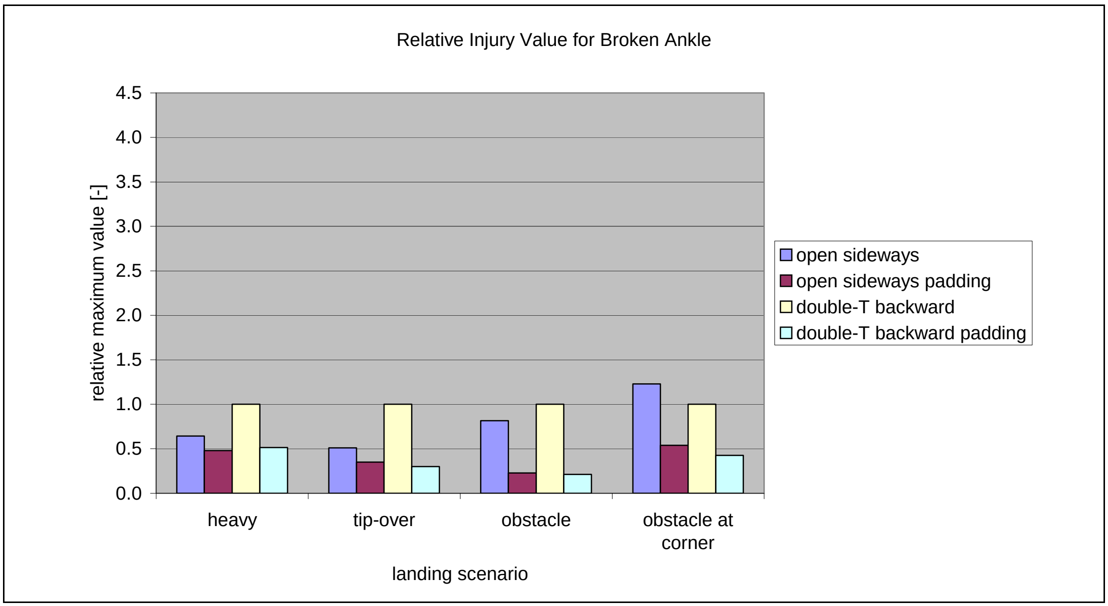


Figure 9 Relative maximum lower tibia dorsiflexion torque resulting from the original and the simulations with foam padding modelled.

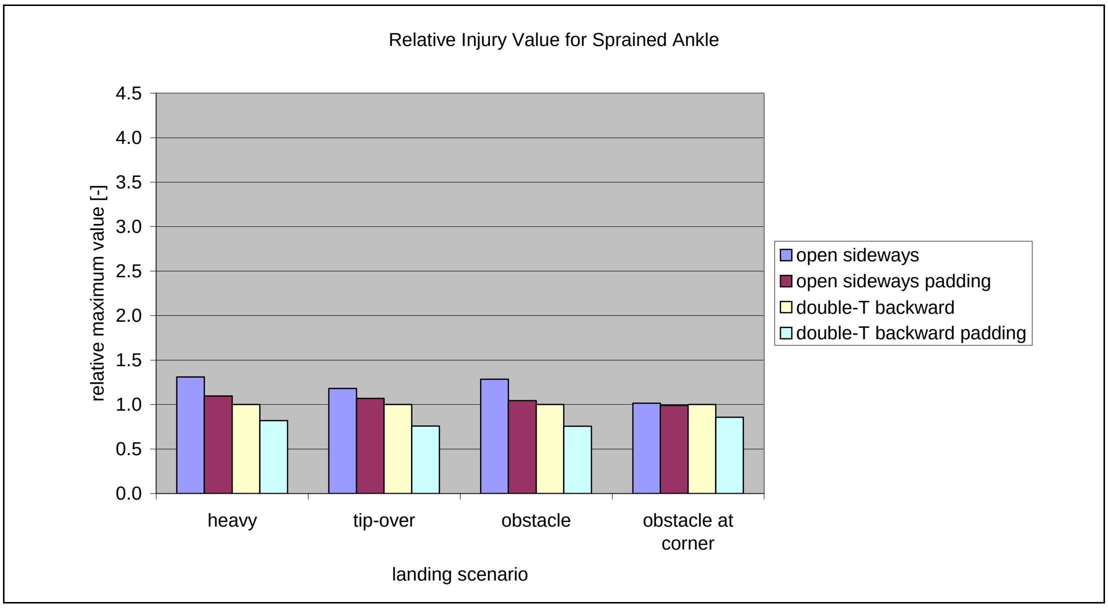


Figure 10 Relative maximum of anterior talofibular ligament, posterior talofibular ligament and calcaneofibular ligament strain resulting from the original simulations and the simulations with foam padding modelled.

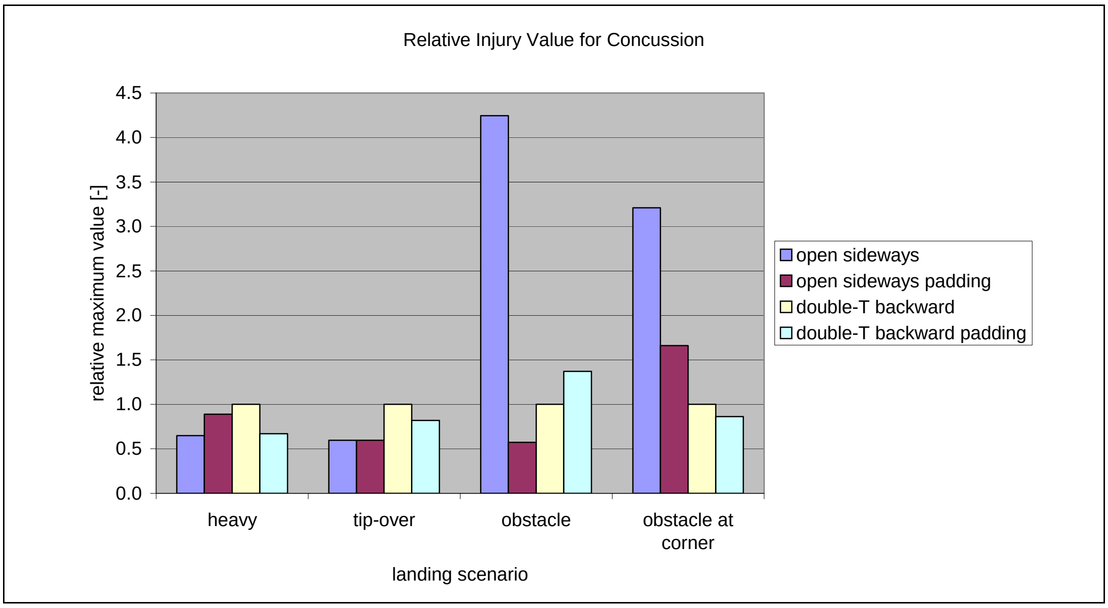


Figure 11 Relative maximum of the resultant head angular and linear accelerations resulting from the original simulations and the simulations with foam padding modelled.

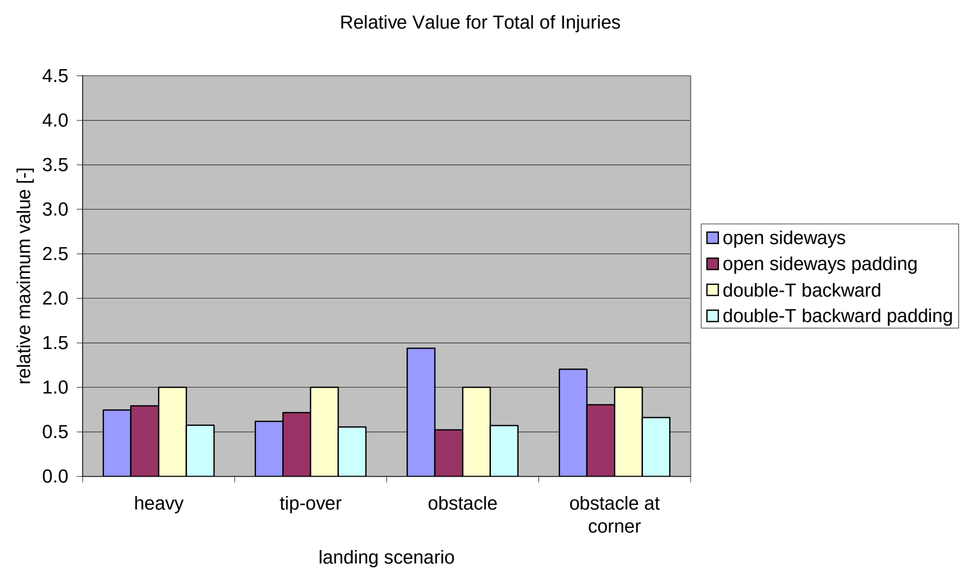
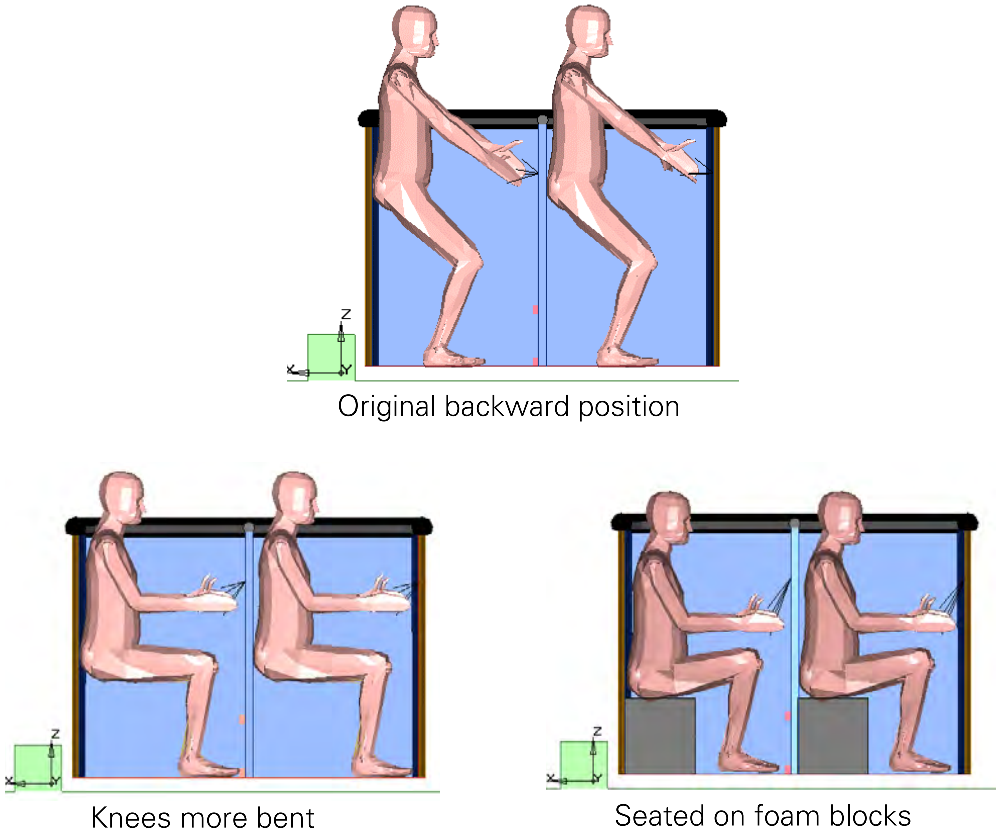


Figure 12 Relative maximum injury value for the total of injuries resulting from the original simulations and the simulations with foam padding modelled.

5 Different Passenger Landing Positions

Variations in the passenger landing positions were only made for the backward position in the double T-partitioned basket together with foam padding. In the sideways position in the open basket there is no space left to bend the knees more, nor for a seating position on foam blocks. The two different passenger's landing positions and the original backwards landing position in the double T-partitioned basket are shown in Figure 13.



Original backward position

Knees more bent

Seated on foam blocks

Figure 13 Simulated passenger landing positions.

The specifications of the foam block were provided by Lindstrand Ltd, see Table 1. For the upper foam of the block part no material specifications could be obtained from the manufacturer, therefore the foam type of the inner sides padding was adopted. The thickness and the stress-strain characteristic of the foam block were incorporated in the contact definition between the human models and the block models. In reality, the foam blocks are covered by a cordura fabric to protect the foam against wear and tear. However, as for the foam padding, the coverings of the foam blocks were not modelled. The specifications of the foam blocks are given in Table 2.

Table 2 Specifications of the foam block.

Part of Foam Block	Height [mm]	Width [mm]	Length [mm]	Foam Type
Upper	50	300	=compartment length	K424[1, 2]
Lower	275	300	=compartment length	K430 [1]

1. Manufactured by Keeling Rubber & Plastics Ltd.
2. No material specifications could be obtained from the manufacturer, therefore foam type K424 was adopted for the foam block model.

Only two human models were positioned in the basket model, because it was impossible to insert four human models into the basket, because of the shoulder width. However, a vertical plane was modelled from the back to the front side of the basket to account for the contact with the side-seated passenger. The two human models were positioned at the right back and right front side of the double T-partitioned basket. In the original simulations with the double T-partitioned basket the calculated maximum injury criteria values were for most criteria and most of the cases found in the human model seated at the right back side. The remaining calculated maximum injury criteria values for the double T-partitioned basket in the original simulations were found in the human model at the right front side. Therefore, the relative injury values resulting from the simulations with the different passenger positions can still be compared to that of the original simulations.

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. In the simulations in which the human models were seated on a foam block no leg muscle activity was prescribed, since it was assumed that passengers are relaxed when they are seated on a foam block.

The effect of the two different landing positions on the relative injury values for all the landing scenarios is shown in Figure 14 to Figure 18. 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 19. Figure 19 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 the tip-over, obstacle and obstacle at corner landings. However, the foam block significantly increased the relative injury value for concussion for all landing scenarios. This was caused by the impact on the ground causing the heads of the passengers to be at height of the basket rim instead of their necks. Consequently, their heads were impacted against the basket rim and also by the impact to the pelvis from the foam block resulting in a higher head upward acceleration. In the position with the knees bent at 90 degrees the relative injury value for a sprained ankle was significantly increased for all landing scenarios, and the relative injury value for concussion was significantly increased in the obstacle at corner landing.

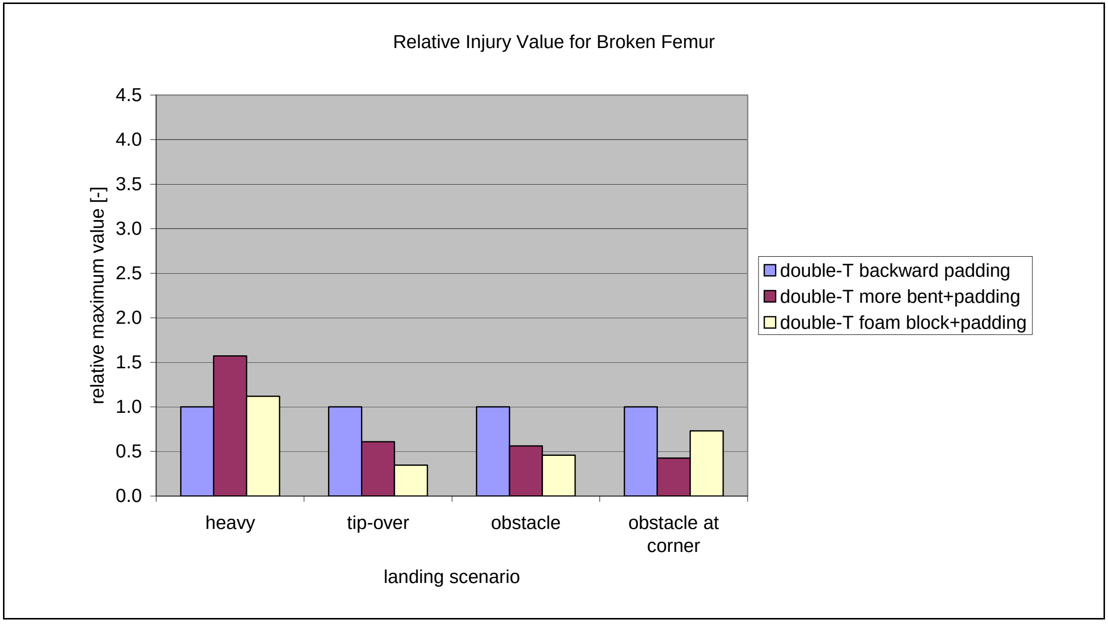


Figure 14 Relative maximum transverse femur bending moment resulting from the simulations with foam padding, the simulations in which the passengers have their knees more bent, and the simulations in which the passengers are seated on a foam block.

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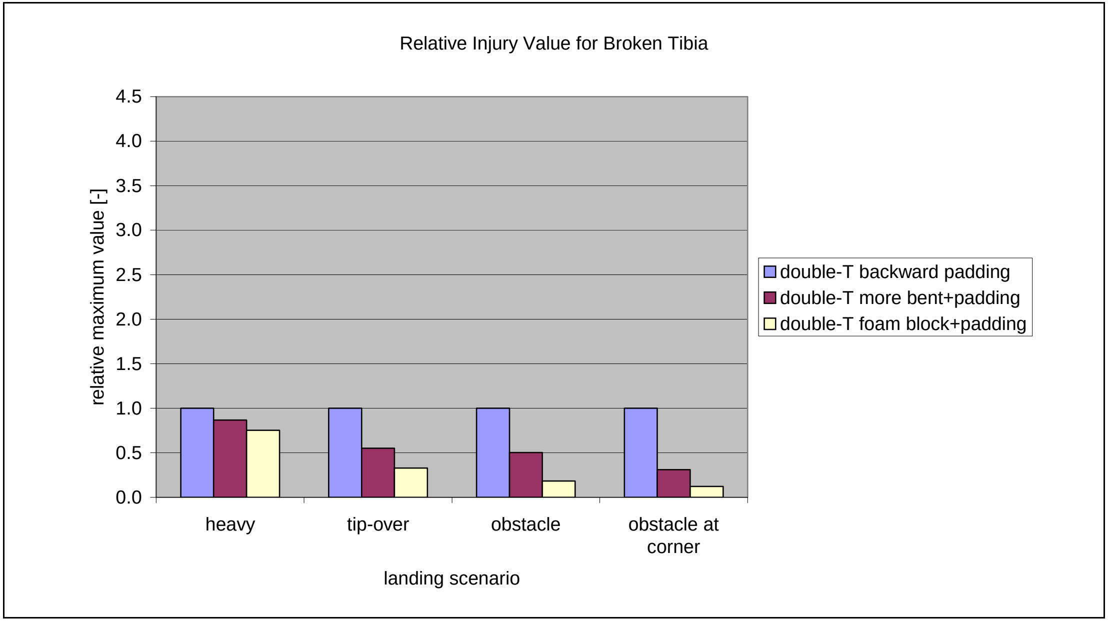

Figure 15 Relative maximum lower tibia compression force resulting from the simulations with foam padding, the simulations in which the passengers have their knees more bent, and the simulations in which the passengers are seated on a foam block.

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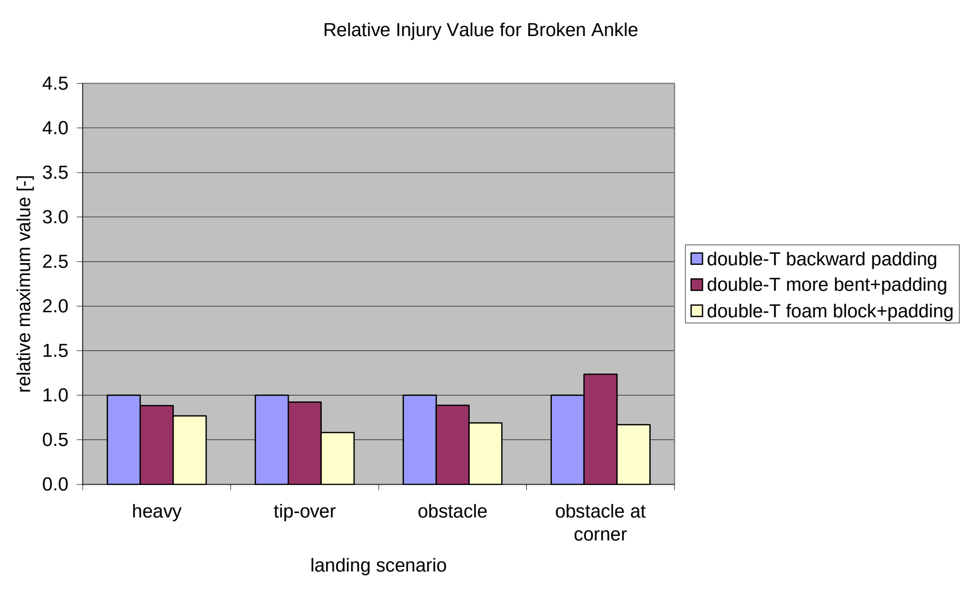

Figure 16 Relative maximum lower tibia dorsiflexion torque resulting from the simulations with foam padding, the simulations in which the passengers have their knees more bent, and the simulations in which the passengers are seated on a foam block

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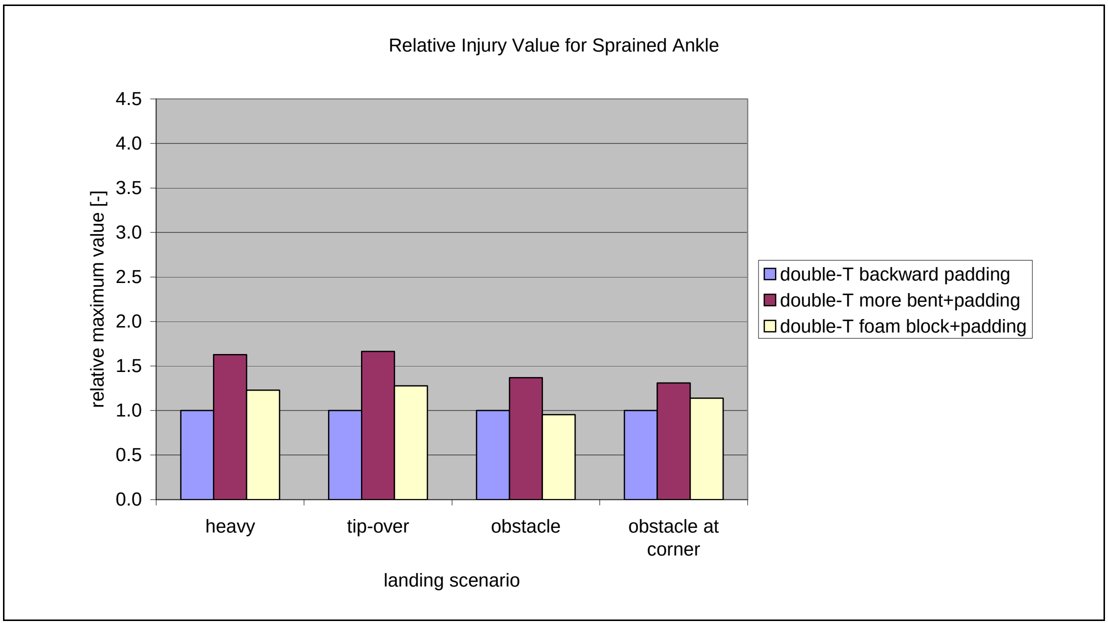

Figure 17 Relative maximum of anterior talofibular ligament, posterior talofibular ligament and calcaneofibular ligament strain resulting from the simulations with foam padding, the simulations in which the passengers have their knees more bent, and the simulations in which the passengers are seated on a foam block.

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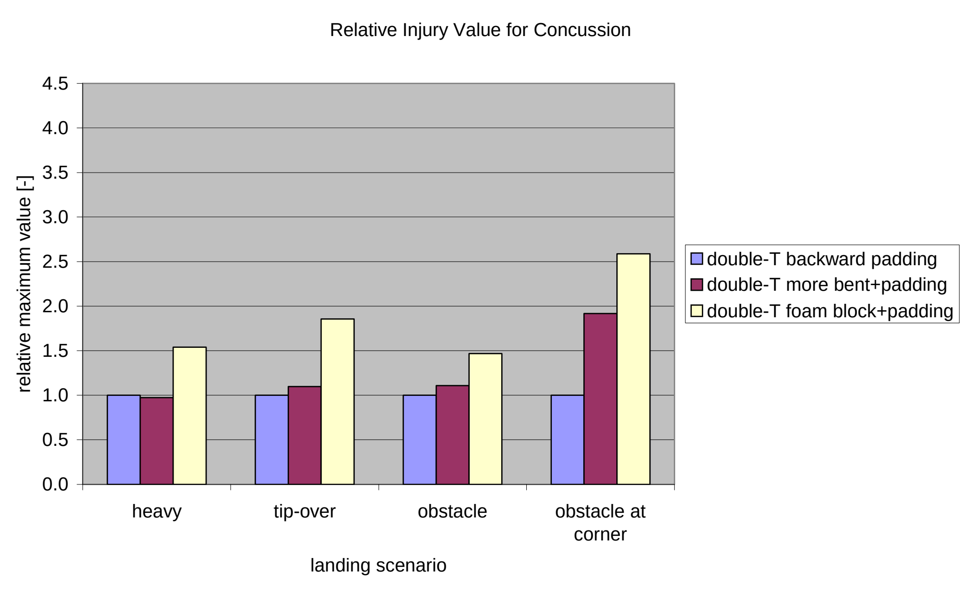

Figure 18 Relative maximum of the resultant head angular and linear accelerations resulting from the simulations with foam padding, the simulations in which the passengers have their knees more bent, and the simulations in which the passengers are seated on a foam block.

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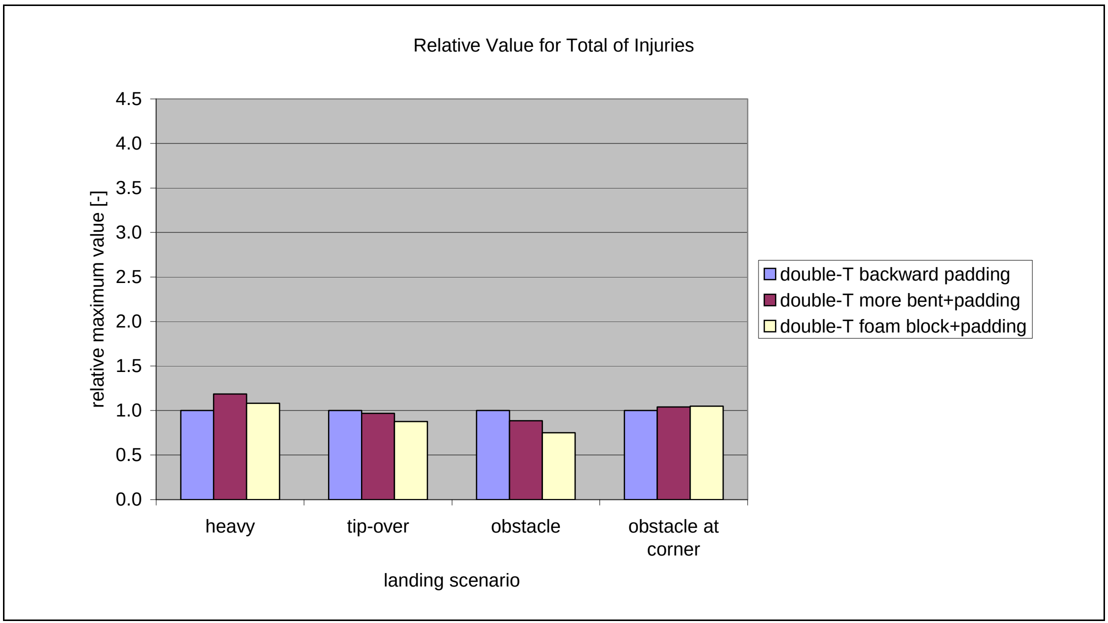

Figure 19 Relative maximum injury value for the total of injuries resulting from the simulations with foam padding, the simulations in which the passengers have their knees more bent, and the simulations in which the passengers are seated on a foam block.

6 Conclusions

From the simulation results the following can be concluded about the effect of the current protection strategies on the injury risk for the sideways position in the open basket and the backward position in the double T-partitioned basket:

- The effect of skids (decreased friction between basket and the ground) did not significantly affect the safety of the passengers either in the open or in the double T-partitioned basket. However, the modelling of the skids was simplified, since the real effects of skids on the landing deceleration of the basket are not known.
- Foam padding at the basket floor, inner sides and rim seems to significantly increase the safety for passengers in a double T-partitioned basket in the backward position for all simulated landing scenarios (heavy, tip-over, obstacle and obstacle at corner landing).
- In the open basket in the sideways position the foam padding seems to significantly increase the safety of the passengers for the obstacle and obstacle at corner landing. The foam padding did not significantly increase the safety of the passengers in the open basket in the heavy and tip-over landing.
- Having the knees bent at 90 degrees instead of 45 degrees in the backward position in the double T-partitioned basket seems not to significantly affect the safety of the passengers. The risks of a broken femur and broken tibia were significantly decreased for the tip-over, obstacle and obstacle at corner landing, but the risk of a sprained ankle was significantly increased for all landing scenarios. Also, the risk of a concussion was significantly increased in the obstacle at corner landing caused by the head contacting the basket rim.
- A backward seating position on a foam block in the double T-partitioned basket is not significantly safer than a backward standing position, except for the obstacle landing. The risks of a broken femur, broken tibia and broken ankle were decreased for the tip-over, obstacle and obstacle at corner landing, but the risk of concussion was increased due to the head contacting the basket rim.

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Section 5 Recommendations

1 From this Study

From the simulation results and the review of the current methods to protect the passengers during hot-air balloon landings the following is recommended:

- For passengers in an open basket it is recommended to adopt a sideways landing position at the front side of the basket with the fuel cylinders installed at the back of the basket as shown in Section 3 Figure 4.
- For passengers in a double T-partitioned basket it is recommended to adopt a backwards landing position as is shown in Section 3 Figure 5.
- It is recommended to let the most vulnerable passenger in an open basket in a sideways position be at the front of the row of passengers and the strongest at the back.
- It is recommended to let the most vulnerable passengers in a double T-partitioned basket be in the front compartments of the basket and the strongest passengers in the back compartments. (Counter-intuitive but see Section 3.3 Discussion).
- For both the sideways landing position in the open basket and the backwards landing position in the double T-partitioned basket, it is recommended for the passengers to bend their knees, but less than 90 degrees, see Section 4, Figure 13.
- It is highly recommended to apply foam padding to the basket floor, inner sides and rim.
- For passengers in a backward seating position on a foam block as is shown in Section 4, Figure 13, it is recommended to apply extra protection to the basket that reduces the impact loading to the head from contact with the basket side/rim.

It must be noted that the above recommendations are based on an open basket with a size of 1·22 x 1·62 m and a double T-partitioned basket with a size of 1·48 x 2·56 m, both with a stiff frame and rigid walls. It is not known whether the recommendations for the open basket also count for an open basket in which there is enough space for the passengers to be all in a backward position, like in the double T-partitioned basket. Also, it must be noted that it is not known, whether the above recommendations also count for a flexible basket, since the simulations were performed with a rigid (worst case) basket.

2 For Further Research

The following is recommended for further research on protecting passengers during hot-air balloon landings:

- It is recommended to also model the most common flexible basket for the cases simulated in this study. If the results of these simulations show that the recommendations in Section 5.1 also count for the flexible basket, these recommendations can be used to develop advice for balloon operators on the best methods for protecting passengers during landings.

NOTE: This recommendation was accepted and results included within this Paper under Section 6.

- It is recommended to test the effects of skids on the movement of the basket experimentally. Then the measured basket movements with and without skids can be used in numerical simulations to study the real effects of skids on the passengers' safety.
- It is recommended to optimise the injury reduction of the foam padding (density, energy absorption and thickness) at the basket floor and inner sides by using finite element simulations of a human model impacting the padding. For the finite element simulation the exact material properties of the foam padding should be determined by material testing.
- It is recommended to optimise the seating height and seating position of the passengers by numerical simulations. The height of the currently used seating block is so low that the passengers cannot damp the impact from the basket by using their leg muscles. A foam-padded roll to lean on or a high foam block to sit on as shown in Figure 1 might be safer for the passengers than the currently used foam block shown in Section 4 Figure 13. Also, a high foam block is easier for older people to get seated on and to get up from than a low seating block.
- In addition, it is recommended to optimise the foams (density, energy absorption and thickness) that are used for the foam-padded roll, the foam block and the rim by numerical simulations and material testing.
- For a low seating position it is also recommended to optimise the foam padding of the basket rim in order to decrease the head impact. This can be done by performing impact tests using a dummy head form (as is used for pedestrian safety testing), but also by finite element simulations of the dummy head form impacting the rim and material testing.

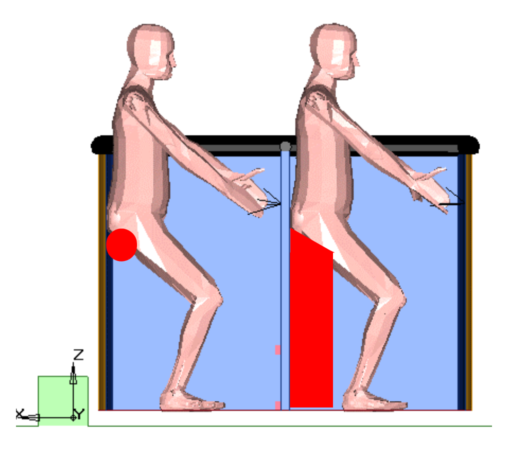

Figure 1 Examples of a foam padded roll (left passenger) to lean on and a high foam block (right passenger) to sit on during the landing.

Section 6 Follow-up Study: Effect of Basket Flexibility

1 Introduction

Thusfar, the basket has been assumed rigid. To investigate the influence of the basket flexibility, a follow-up study was performed. The follow-up study is described in this section.

2 Objective

The objective of the follow-up study was to evaluate the effect of the basket flexibility on the safety of the hot-air balloon passengers during landings for the most flexible open and double T-partitioned basket that are equal to the baskets that were chosen in the first study (see Section 2 paragraph 4.2).

3 Approach

For creating flexible basket computer models information about the force-deformation characteristics of the open and double T-partitioned baskets was needed. Since no information about the force-deformation characteristics of baskets was available, experimental deformation tests were performed with both basket types.

To create flexible basket computer models, the rigid basket models were adapted. The flexible basket models were each validated using the experimentally determined force-deformation characteristics.

The effect of the basket flexibility on the passengers' safety was determined by repeating the simulations performed in Section 3. First, the landing test was simulated (see Section 3 paragraph 1.5) in order to see whether a landing simulation with the flexible basket resulted in the same acceleration as was measured in the real basket. Next, the simulations of the four most dangerous landing scenarios with the passengers in sideways and backwards landing positions (see Section 3 paragraph 2) were repeated with the flexible basket models. The results of all these landing simulations were compared to those of the rigid baskets, described in Section 3 paragraph 2.

4 Determination of the Baskets Deformation Characteristics

An open basket and a double T-partitioned basket of a similar size to the ones that were modelled were borrowed from A3 Ballon B.V., see Figure 1. Unfortunately, no baskets were available of exactly the same size as those modelled. Information about the types and sizes of the baskets that were tested is given in Table 1.

Figure 1 Baskets used to experimentally determine the force-deformation characteristics. Left: Open basket; Right:Double T-partitioned basket.

Table 1 Basket types and sizes.

Basket Type	Size [m]	Contructor	Type	Serial No
Open	1·10 x 1·55	Cameron Balloons Ltd.	N-105	3612
Double T	1·57 x 2·18	Cameron Balloons Ltd.	A-180	10666

All tests to determine the force-deformation characteristics of the baskets were performed by TNO Building & Construction with assistance of TNO Automotive. Before the tests the cylinders were taken out of the baskets. Each basket was deformed by a hydraulic jack pushing at the inner side of the walls in various configurations. A wooden block with an area of 15 x 15 cm was placed between the hydraulic jack and the basket walls in order not to damage the wicker. The chosen deformation configurations coincide with deformations which can happen during landings. The various deformation configurations are schematically shown in Figure 2. The front views show the directions which the hydraulic jack pulled inside the baskets. The top views show at which heights the baskets were pushed from the inside. In deformation configuration C (diagonal) a smaller wooden block was used in order to fit in the corners of the baskets. Figure 3 shows the hydraulic jack in two of the deformation configurations.

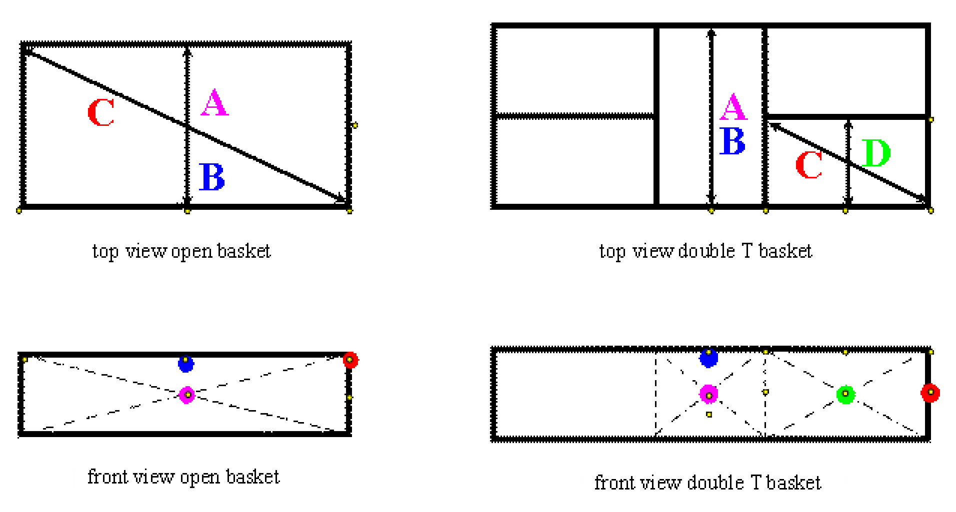

Figure 2 Schematic drawing of deformation configurations of the open and double T-partitioned baskets.

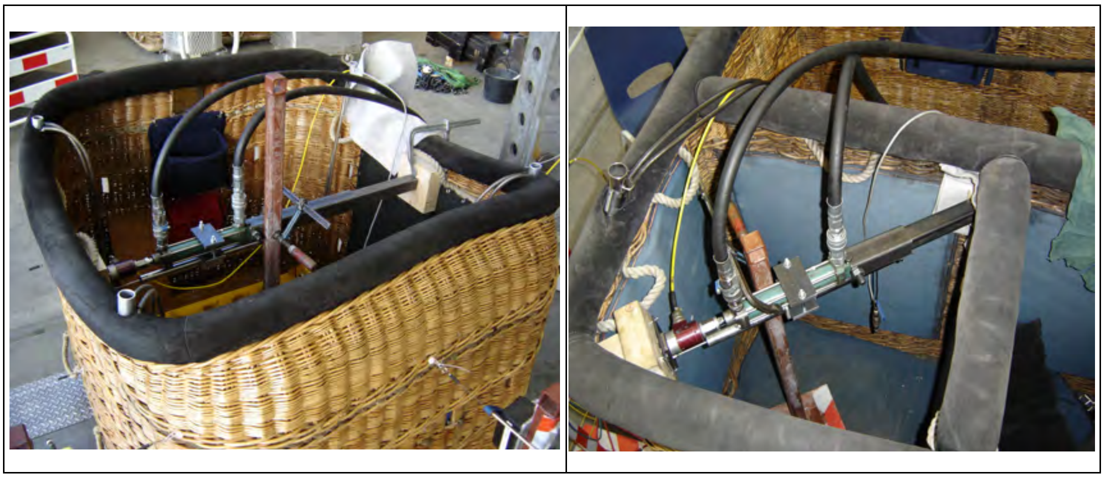

Figure 3 Hydraulic jack in two different deformation tests: Left: Open basket in deformation configuration B; Right: Double T-partitioned basket in deformation configuration C.

Each deformation configuration was started with pilot tests to see what deformation could be reached without damaging the wicker walls of the baskets. Then tests were performed at velocity rates: 0·2 m/s, 0·6 m/s and 1·2 m/s. Table 2 shows a summary of all the deformation tests that were performed. Also, a pilot test was performed at a rate of 4·8 m/s, however it was not possible to measure the force correctly anymore. Also, a pilot test was performed at 2·4 m/s, however not much difference was seen between the maximum force at 2·4 m/s and 1·2 m/s. Therefore, it was decided not to go higher than 1·2 m/s. A deformation rate of 2 m/s would have been preferred, since this was expected for the humans in the basket during the simulated landing situations.

Table 2 Summary of the basket deformation that were performed.

Test Series	Basket type	Deformation configuration	Deformation velocities [m/s]
1	Open	A	0·2, 0.6 and 1·2
2	Open	B	0·2, 0.6 and 1·2
3	Open	C	0·2, 0·6 and 1·2
4	Double T-partitioned	A	0·2, 0·6 and 1·2
5	Double T-partitioned	B	0·2, 0·6 and 1·2
6	Double T-partitioned	C	0·2, 0·6 and 1·2
7	Double T-partitioned	D	0·2, 0·6 and 1·2

Displacement transducers were used to measure the displacements in x- and y-direction at several positions at the outside of the basket walls. These positions are shown as yellow blocks in Figure 4. The measured displacements were at points where the largest displacements occurred, so for each deformation configuration different displacement measurements were performed. Figure 4 shows the displacement transducers at the open basket in deformation configurations A and C.

Figure 4 Open basket during deformation tests. Left: Deformation configuration C; Right: Deformation configuration A.

5 Development and Validation of Flexible Basket Models

The models of the open and double T-partitioned basket developed in the first study were adapted to make them flexible. This was done by using the finite element method to model the walls of both baskets. Also for the compartment walls of the double T-partitioned basket the finite element method was used. In order to reduce the calculation times, the meshes of the flexible basket models were made coarser.

Since most baskets have a wooden plate at the bottom (including the ones that were used in the deformation tests), the bottom was kept rigid. For the walls an anisotropic material model was used. This material model could best describe the mechanical behaviour of the woven wicker walls of the baskets. The density of the material model was chosen such that the masses of each of the flexible basket models were similar to that of the rigid basket models. As a result the inertia properties were also approximately similar.

The deformation tests of both baskets at velocity rate of 120 mm/s were simulated with the flexible basket models and used for tuning the material parameters. The measured displacement at the location of the push blocks was prescribed to the basket wall, acting on an area similar as the size of the push block. The material parameters (stiffnesses in various directions) were chosen such that the calculated displacements of the basket walls fitted best with the measured displacements. It was not possible to get the calculated displacement exactly the same as the measured displacements, because the modelled baskets and tested baskets are not of exactly the same size and type. However, it was possible to get an approximately similar magnitude and trend in the displacements. The measurements from transducers that were in the range of the measurement error were not used for the validation of the basket model. Figure 5 shows the open basket in deformation configuration A at maximum displacement. The validation results of the flexible basket models with the best fitted material parameters are shown in Appendix E. Simulations, in which the measured force was prescribed as pulling force at the basket models, showed that the calculated displacements were similar to those in the simulations in which the displacement of the push blocks was prescribed. This confirmed that the stiffness of the basket models was comparable to that of the real baskets.

All the force-penetration characteristics between the ground and the basket and between the human models and the baskets were kept the same as in the rigid basket models. To test the flexible basket model impact response on the ground, the simulations of the landing tests (see Section 3 paragraph 1.5) with the flexible open basket model were repeated. The resulting accelerations of the flexible basket model were equal to that of the rigid basket model.

Figure 5 The flexible open basket model in deformation configuration A at maximum displacement.

6 Effect of Basket Flexibility on Passenger Safety

In the simulations of the four most dangerous landing scenarios (as defined in Section 2 paragraph 4.1) with the passengers in the sideways and backwards landing positions (as defined in Section 2 paragraph 4.3), the open and the double T-partitioned rigid basket models were replaced by the flexible basket models. All other conditions, like the contacts, initial basket velocities etc. were kept the same.

Also, in this follow-up study the chance of injuries cannot be calculated from the simulations. So, like in the first study, the simulation results of the different landing positions can only be compared to each other. Unlike in the first study, the basket characteristics are now known. For this reason, more confidence is gained in the maximum injury criteria values resulting from the simulations. For the first study, the maximum injury criteria values were shown in Appendix C, and in Sections 3 and 4 only the relative maximum injury criteria values were shown. In order to easily see the effect of the basket flexibility on the chance of injuries, in this follow-up study the maximum injury criteria values resulting from the flexible basket model are compared to that of the flexible basket model.

The maximum injury values resulting from the simulations with the rigid open basket compared to that with the flexible open basket are shown in Figure 6 to Figure 13. The black horizontal line in each bar diagram again shows the injury tolerance limits given in Section 3, Table 3.

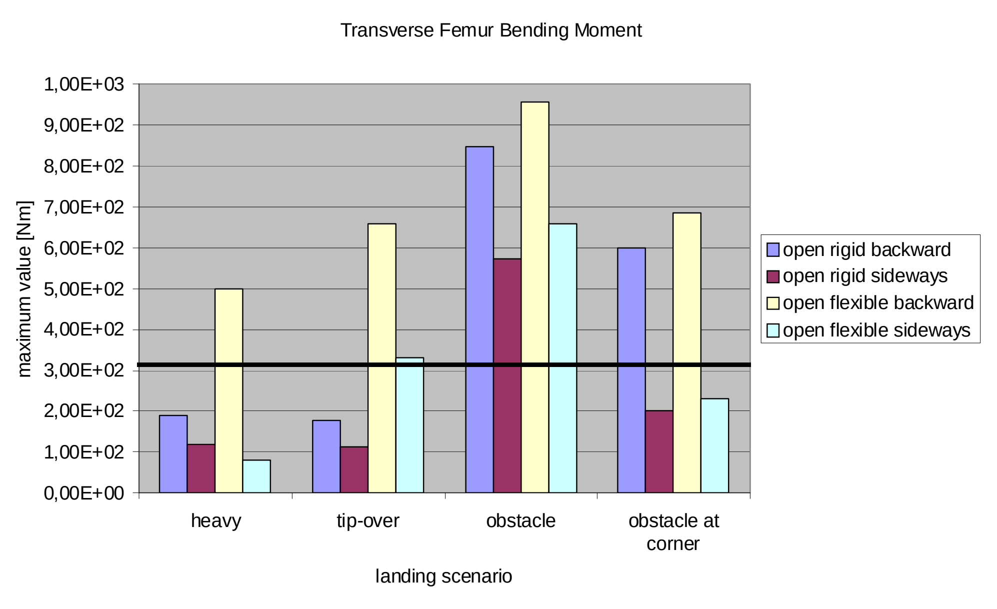

Figure 6 Maximum transverse femur bending moment resulting from the simulations with the rigid and flexible open basket.

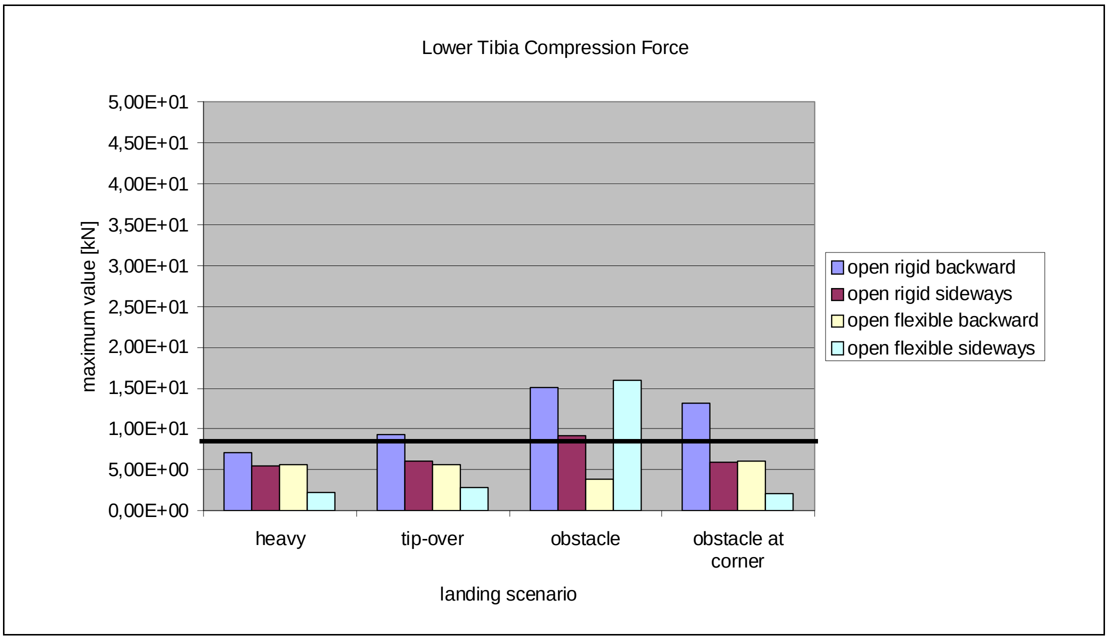

Figure 7 Maximum lower tibia compression force resulting from the simulations with the rigid and flexible open basket.

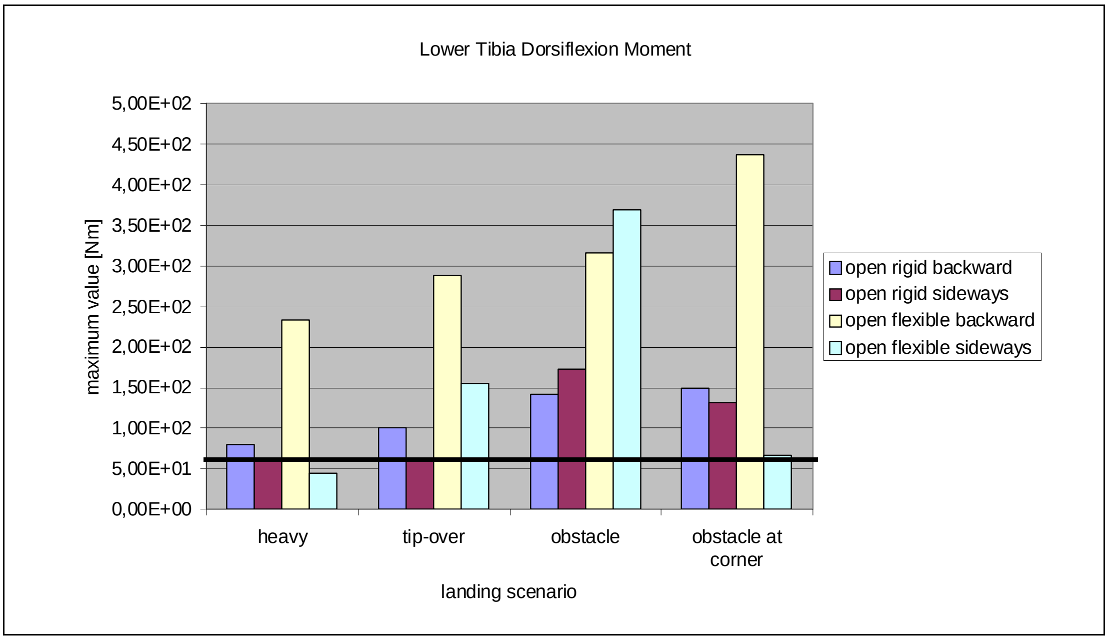

Figure 8 Maximum lower tibia dorsiflexion torque resulting from the simulations with the rigid and flexible open basket.

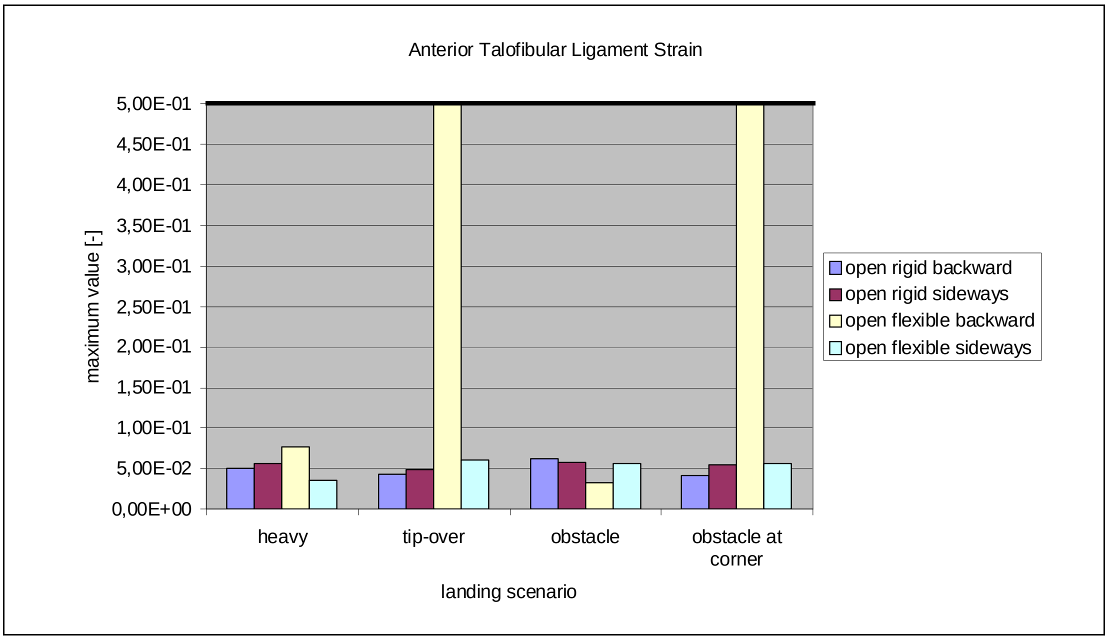

Figure 9 Maximum anterior talofibular ligament strain resulting from the simulations with the rigid and flexible open basket.

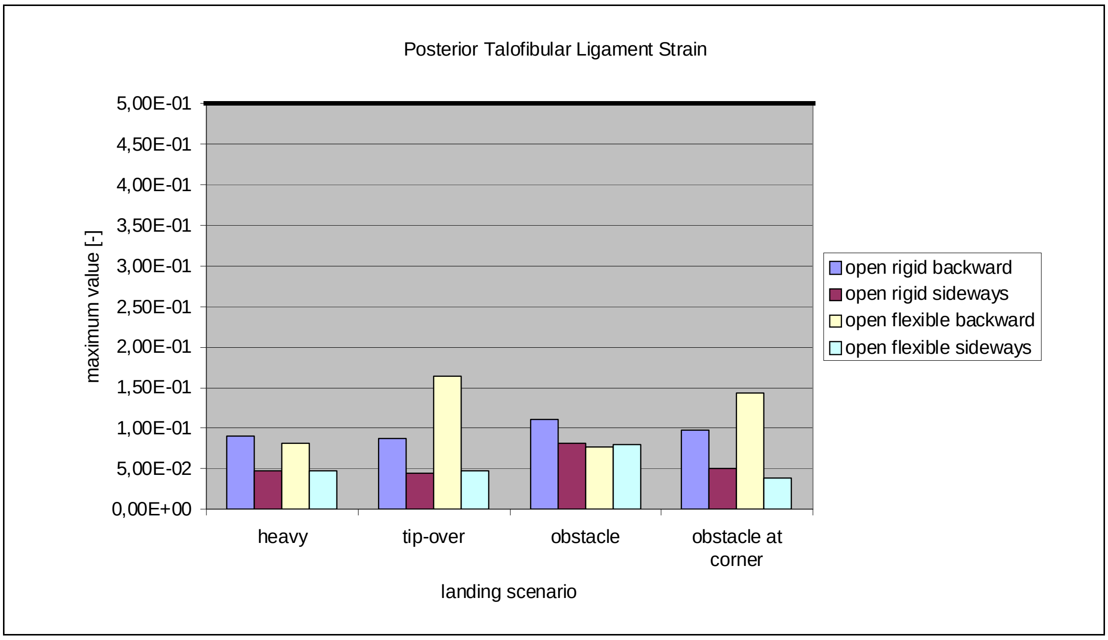

Figure 10 Maximum posterior talofibular ligament strain resulting from the simulations with the rigid and flexible open basket.

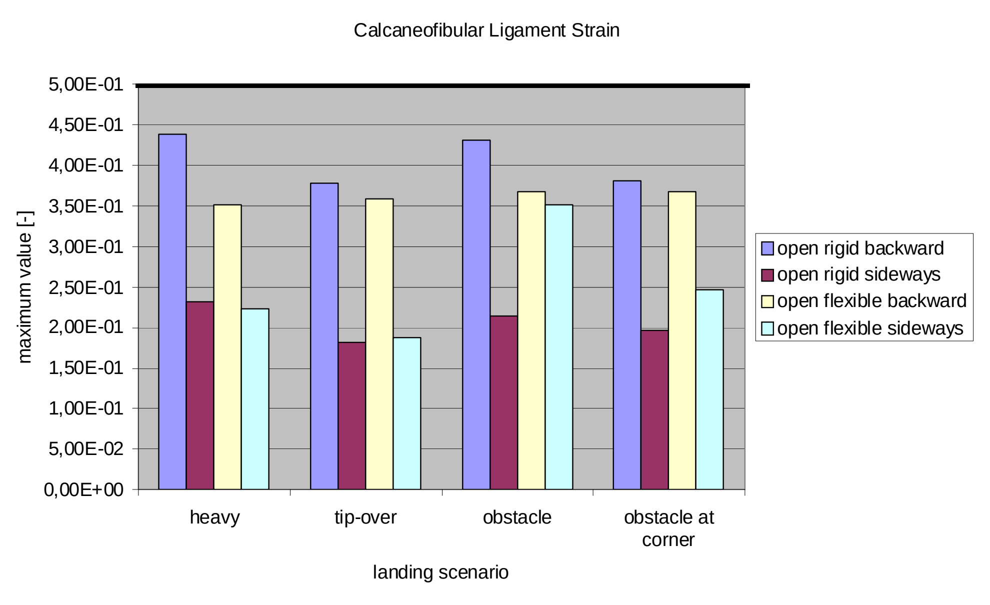

Figure 11 Maximum calcaneofibular ligament strain resulting from the simulations with the rigid and flexible open basket.

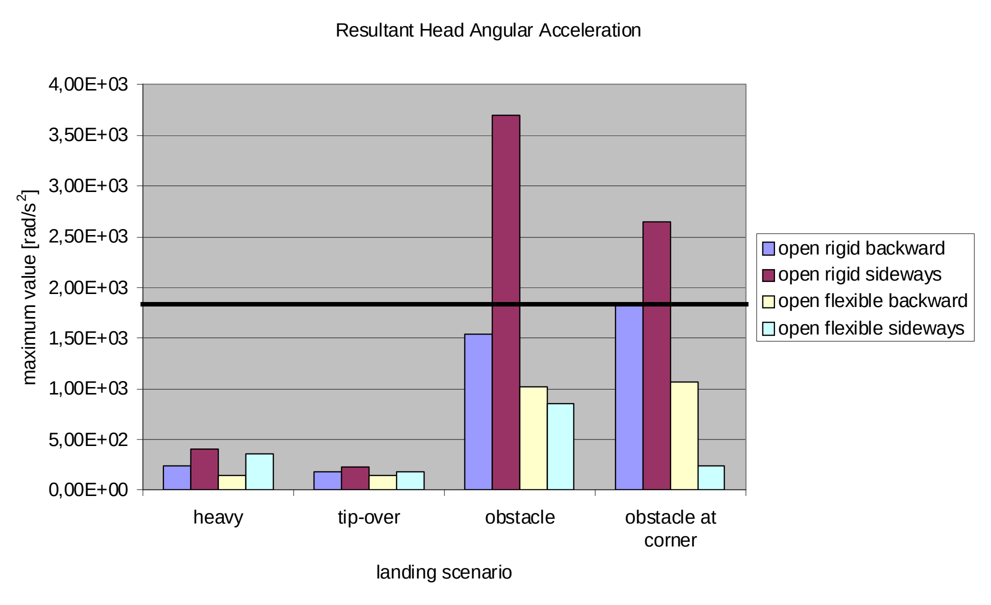

Figure 12 Maximum resultant head angular acceleration resulting from the simulations with the rigid and flexible open basket.

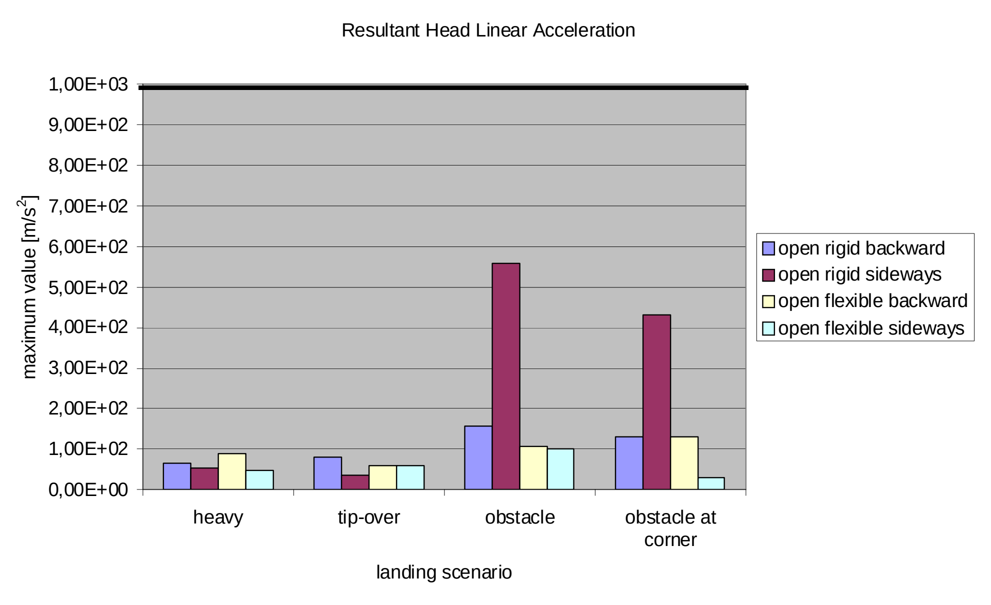

Figure 13 Maximum resultant head linear acceleration resulting from the simulations with the rigid and flexible open basket.

The maximum injury values resulting from the simulations with the flexible double T-partitioned basket compared to that with the rigid double T-partitioned basket are shown in Figure 14 to Figure 21. The black horizontal line in each bar diagram again shows the injury tolerance limits given in Section 3, Table 3.

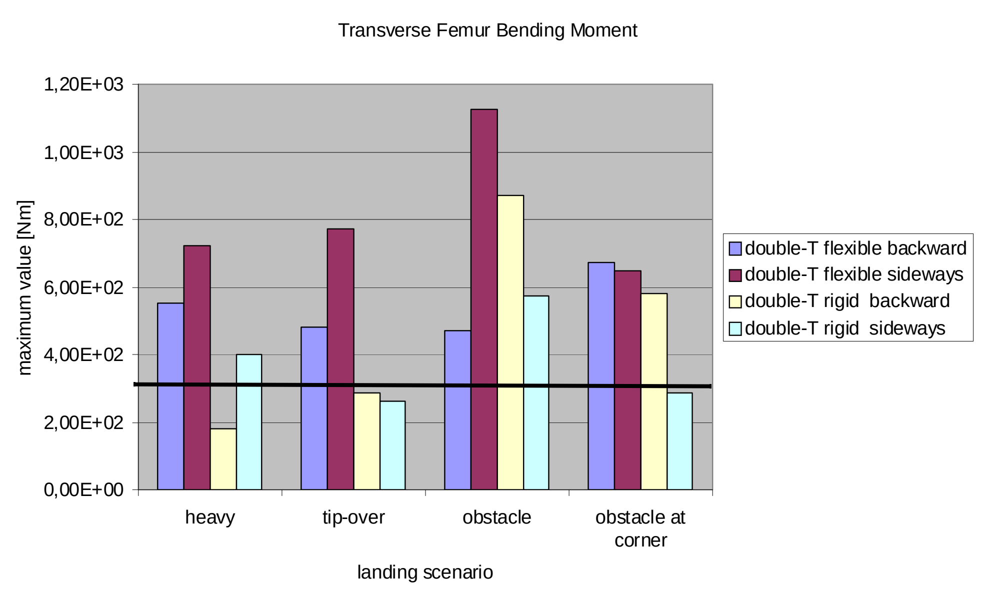

Figure 14 Maximum transverse femur bending moment resulting from the simulations with the rigid and flexible double T-partitioned basket.

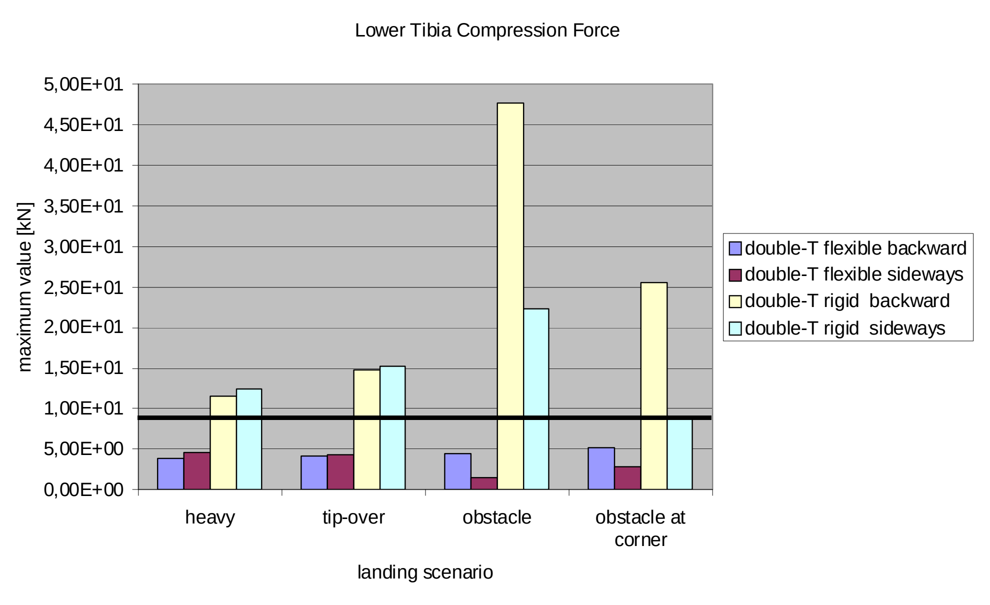

Figure 15 Maximum lower tibia compression force resulting from the simulations with the rigid and flexible double T-partitioned basket.

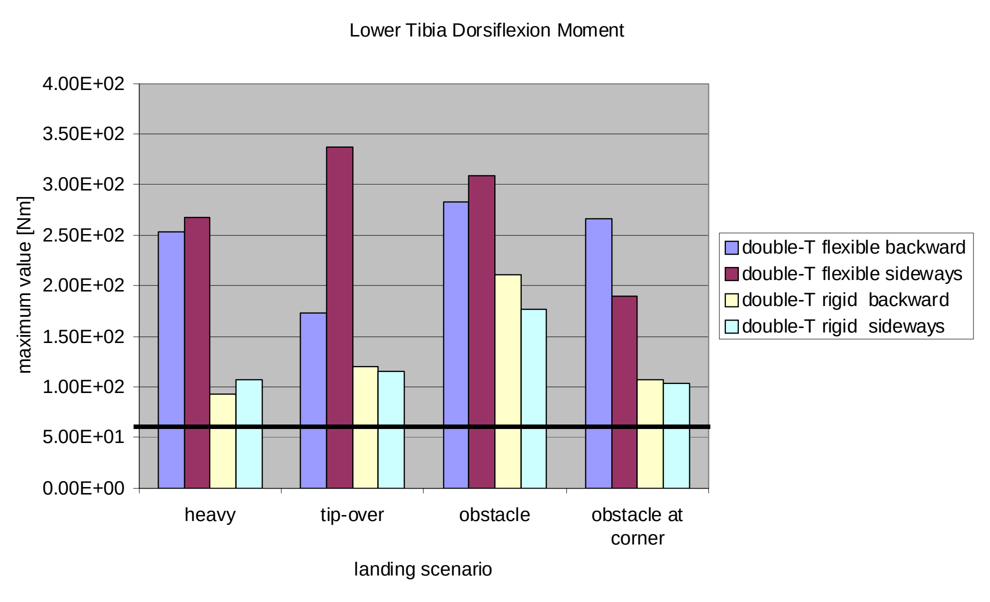

Figure 16 Maximum lower tibia dorsiflexion torque resulting from the simulations with the rigid and flexible double T-partitioned basket.

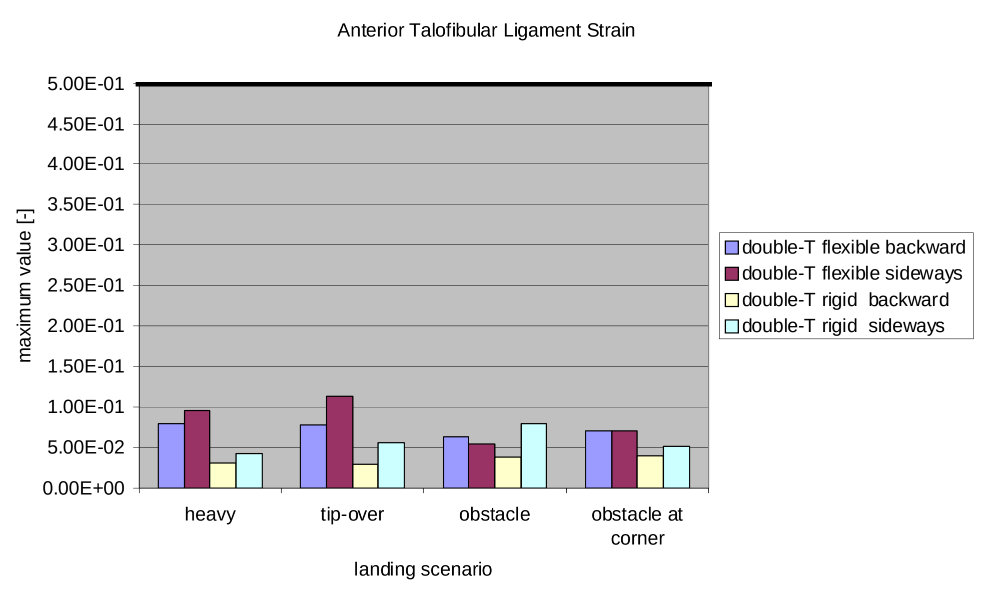

Figure 17 Maximum anterior talofibular ligament strain resulting from the simulations with the rigid and flexible double T-partitioned basket.

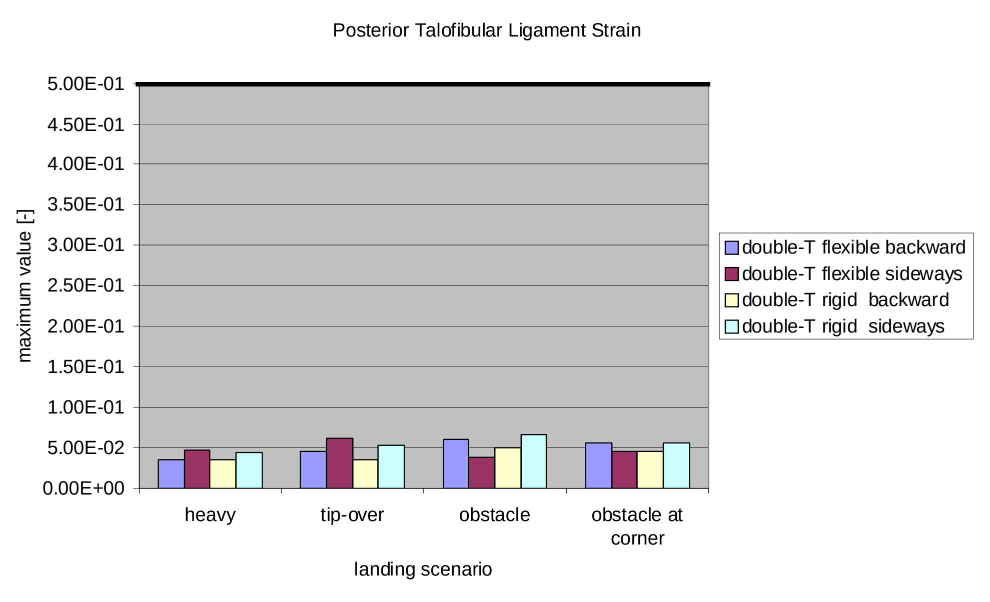

Figure 18 Maximum posterior talofibular ligament strain resulting from the simulations with the rigid and flexible double T-partitioned basket.

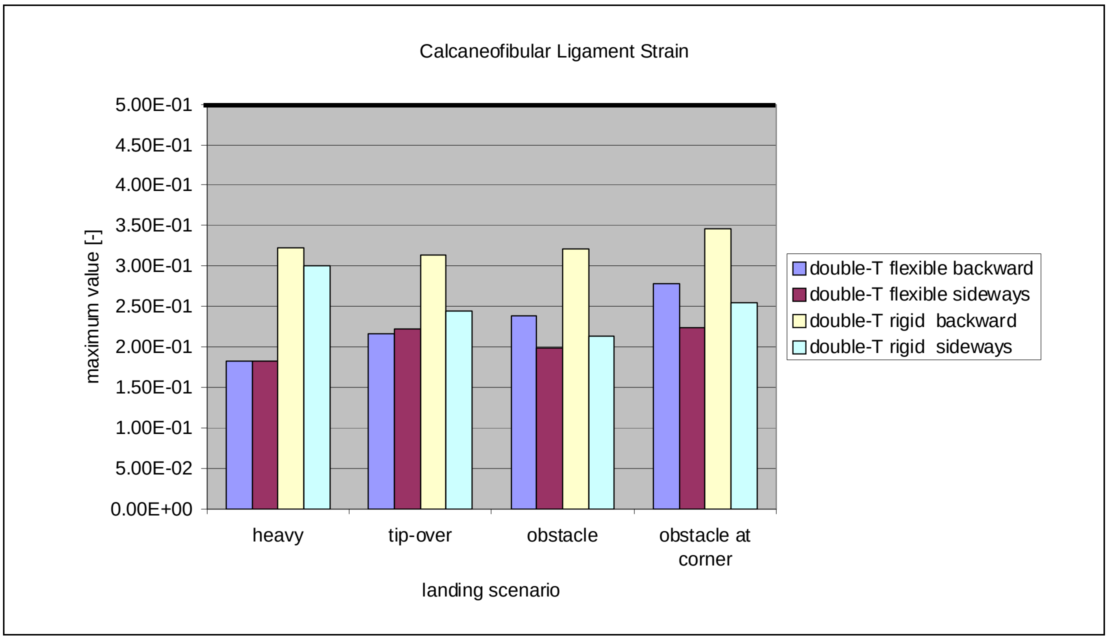

Figure 19 Maximum calcaneofibular ligament strain resulting from the simulations with the rigid and flexible double T-partitioned basket.

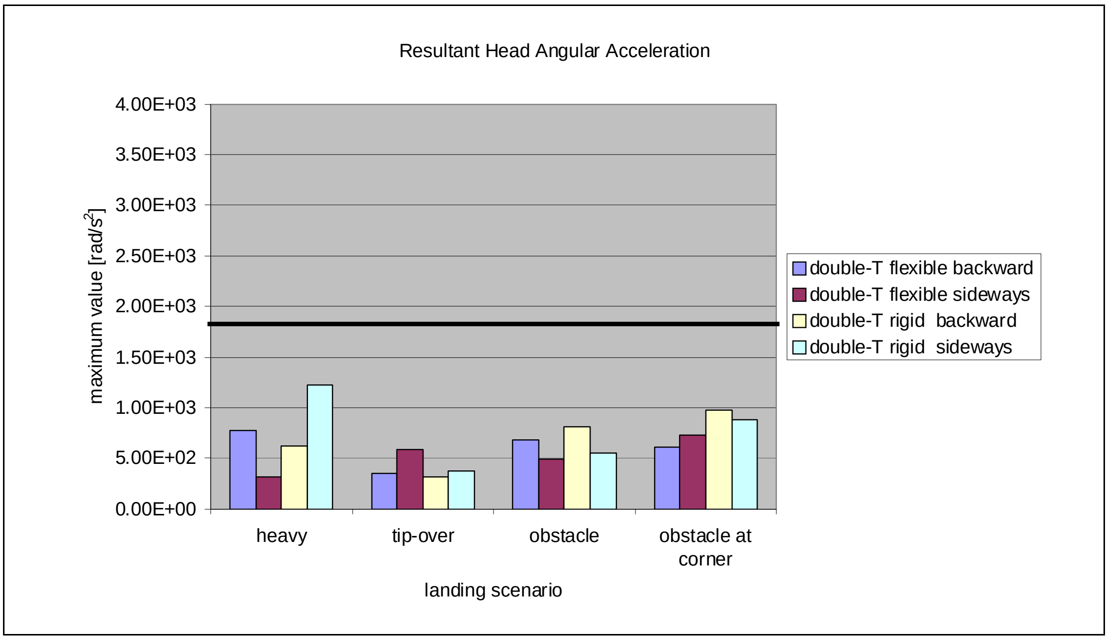

Figure 20 Maximum resultant head angular acceleration resulting from the simulations with the rigid and flexible double T-partitioned basket.

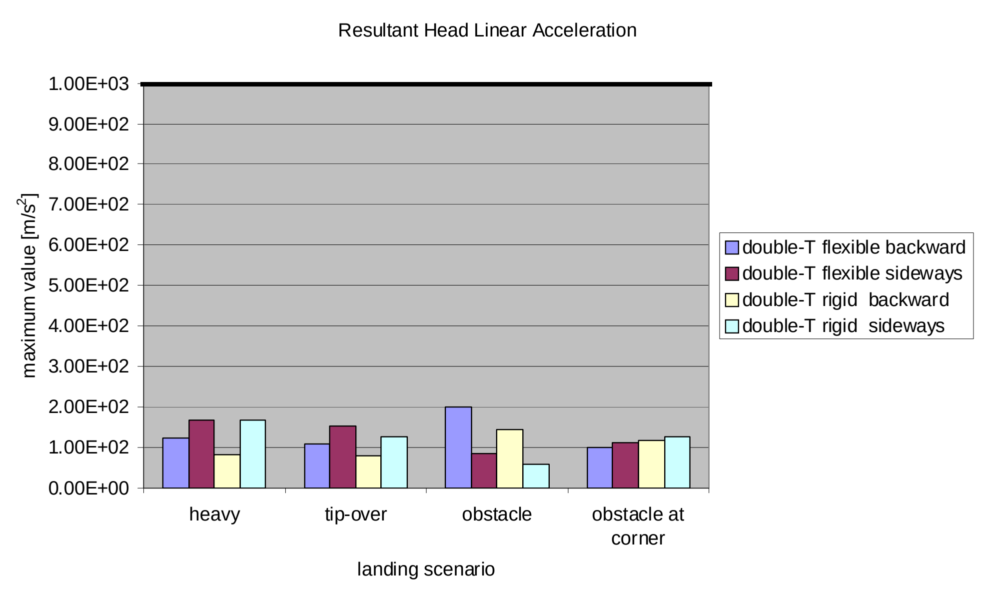

Figure 21 Maximum resultant head linear acceleration resulting from the simulations with the rigid and flexible double T-partitioned basket.

In order to compare the overall safety of each landing position per landing scenario for the flexible basket models, the relative value for the total of injuries was calculated. The relative value for the total of injuries was calculated the same way as for the rigid basket models (see Section 3 paragraph 2). For this, the maximum injury criteria values 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. Next, a relative value for the injury risk was calculated for each kind of injury given in Section 3, Table 3 (femur fracture, tibia fracture, ankle fracture, ankle sprain and concussion) for each simulation with the flexible basket models. The relative injury value for a sprained ankle was defined as the mean of the relative maximum injury criteria values for the strain of the anterior talofibular ligament, posterior talofibular ligament and calcaneofibular ligament (see Section 3, Table 3). The relative injury value for a concussion was defined as the mean of the relative maximum injury criteria values for head angular acceleration and head linear acceleration (see Section 3, Table 3). In the relative value for the total injuries, each kind of injury was considered equally.

Figure 22 shows the relative value for the total injuries for all the flexible basket simulations, as for the rigid baskets in Section 3, Figure 18. As in the first study, it must be noted that the relative values for the total injuries can only be compared qualitatively and not quantitatively. Thus, a relative injury value of 1.2 for a certain position in a certain basket does not mean that the chance of 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.

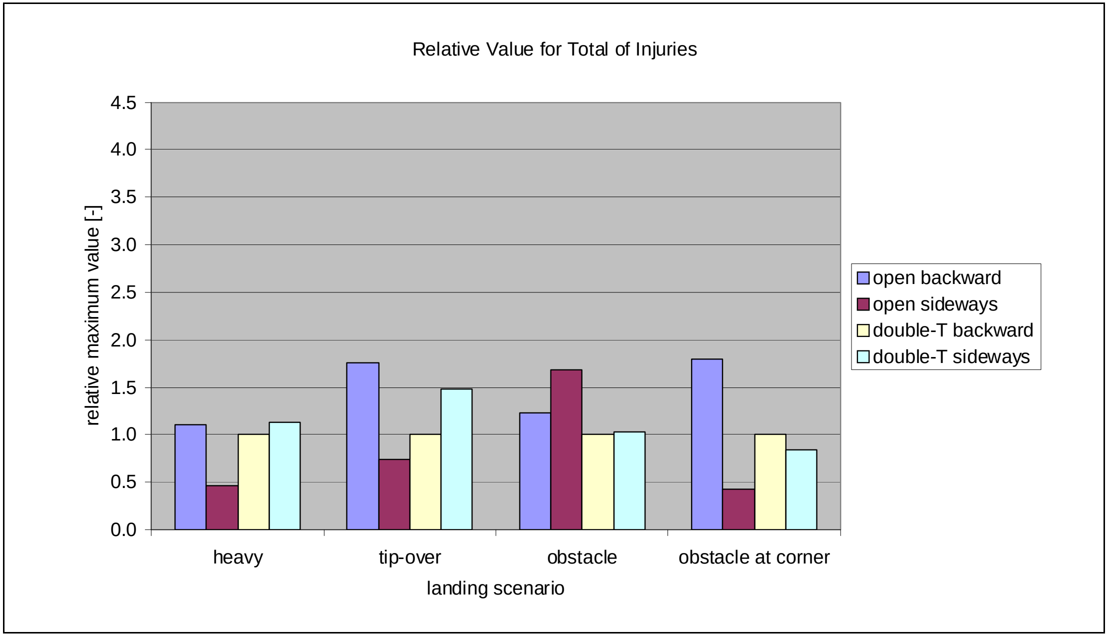

Figure 22 Relative maximum value for the total of injuries resulting from the simulations with the flexible open and double T-partitioned baskets.

7 Discussion

From Figure 6 to Figure 13, Figure 22 and Section 3, Figure 18, it can be seen that in general the same trend can be observed for the flexible open basket as for the rigid open basket. Significant differences in the trends can be seen in some of the landing scenarios for the lower tibia compression force, the anterior talofibular ligament strain and the Head Resultant Accelerations. Also, differences in magnitudes of the injury criteria values between the rigid and flexible open baskets can be seen. The lower tibia dorsiflexion moment resulting from the flexible open basket simulations was in most landing scenarios significantly higher than for the rigid basket and the Head Resultant Accelerations was significantly lower. The differences in injury criteria values between the rigid and flexible basket models can be explained by slight differences in the kinematics of the human models due to the flexible walls. In general the kinematics of the human models in the rigid open basket are similar to that of the flexible open basket. From the simulation results with the flexible open basket it seems that the sideways position is safer than backward, except for the tibia when the basket hits an obstacle at the front side.

From Figure 14 to Figure 21 it can be seen that in general the trend for the flexible double T-partitioned basket seems to be different than for the rigid double T-partitioned basket. Further, the lower tibia dorsiflexion moment resulting from the flexible double T-partitioned basket simulations was in all landing scenarios significantly higher than for the rigid basket. And the lower tibia compression force was significantly lower for the flexible than for the rigid double T-partitioned basket. Also, for the double T-partitioned basket the differences in injury criteria values between the rigid and flexible basket models can be explained by slight differences in the kinematics of the human models due to the flexible walls. However, the relative value for the total of injuries, see Figure 22 and Section 3, Figure 18, only slightly changed. The differences between the backward and sideways landing position for the landing simulations in which the basket hits an obstacle, at the front side or at a corner, are not significant. Thus, from the simulation results of the flexible double T-partitioned basket the backwards landing position seems to be safer than sideways.

The head injury criteria in the flexible basket models are so far below the injury level, that it is doubtful whether these injury criteria should be taken into account in evaluating the safety of the landing position. The reason for the lower values is that no head contact takes place during the simulations with the flexible baskets. Suggestions made during the project meetings to wear a helmet for increasing safety are therefore not supported by the current study. When the head injury criteria are not taken into account, the relative values for the total of injuries will more clearly show that the sideways landing position is safest in the open basket and the backwards landing position is safest in the double T-partitioned basket.

In the flexible double T-partitioned basket the passengers in the front compartments seem to be safer than in the back compartments in all landing scenarios simulated. This conclusion is in line with the conclusion on the rigid double T-partitioned basket. The reason for this is explained in Section 3 paragraph 3.

The reason that Figure 22 and Section 3, Figure 18 hardly show any differences, while differences were shown in the injury criteria values between the human models in the flexible baskets and the rigid baskets, is mainly that the load distributions over the tibia and the femur changed, not so much the kinematics.

The reason that the results of the landing simulations with the flexible baskets are similar to those of the rigid baskets, might be that the flexibility of the baskets is not very much. Though, the open basket that was tested was considered to be one of the more flexible ones, because of its shape and age (it was 10 years old). The double T-partitioned basket was more stiff, because of the compartments and because it was a relatively new one, only 1 year old.

8 Conclusions

From the landing simulations with the flexible basket models the following can be concluded:

- In the open basket the sideways landing position is safer than the backward position, except for the tibia when an obstacle is hit during the landing at the front side of the basket.
- In the double T-partitioned basket the backwards landing position is safer than the sideways position.
- The passengers in the front compartments of the double T-partitioned basket seem to be safer than in the back compartments in all landing scenarios simulated.

Finally, the overall conclusion of this follow-up study is that the flexibility of the basket hardly influences the final conclusions about the safest passenger landing positions based on the rigid basket simulation results in the previous study (reported in Section 5).

Glossary

The explanation of the biomechanical terms used in this report are given below.

anterior	situated in the front part of the body
posterior	situated in the back part of the body
dorsiflexion	turning upward of the foot
femur	thigh-bone
tibia	shin-bone
pelvis	hip-bone
ligament	A band of fibrous tissue that connects bones or cartilages, serving to support and strengthen joints

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Acknowledgements

This study is conducted with the help of many people that are involved in the ballooning business. Therefore, the authors would like to thank Ian Chadwick and Graham Greene for their great help and making this study possible, Simon Forse, Shiralee Colin, Wyn Morgan, Phil Hossack, Tony Pinner, Kenneth Karlstrom, John Davies, Tim Parker, Tony Brown and Tom Sage, for providing information about balloon accidents, balloon landings, passenger positions and protection strategies, Rob Cox for providing the drawings of the baskets, Bob Commander, Alan Carter, Keith Thomas, and Mark Hamment, for their contribution during the meetings, Johannes Kooistra for piloting his balloon during the balloon landing tests, Berend Jan and Sabina Floor for their assistance in the balloon landing tests, Cees van Everdinck for performing the acceleration measurements during the landing tests and A3 Ballon B.V. for the use of their baskets for the basket deformation tests. The authors would also like to thank the balloon operators who were very helpful in providing information about the passenger landing positions during the Bristol Balloon Fiesta 2003.

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Appendix A Balloon Accidents

This data is amalgamated from several sources. There are known inconsistencies in some of the details, however these do not significantly affect the overall analysis.

Table 1 UK hot-air balloon accidents caused by hard landings between January 1993 and January 2003 .

Date	Landing Scenario	Balloon & Basket Type	Landing Positions	Passengers Injuries
13 Mar 1993	After firm touch down, basket began to drag immediately. The dragging became erratic and violent so that the 2 passengers were thrown out of basket. When the basket going up again the third passenger was thrown out. Surface wind higher than forecast of 10-12 knots.	Cameron N-90, G-TEDF. Open.	Unknown, training flight.	3 crew: 1 seriously injured and 2 minor.
29 Apr 1993	Estimated actual approach speed 8 knots just before touchdown. Change in wind velocity turned balloon and a corner impacted and dug into soft ground. Sudden deceleration in abnormal direction caused passengers to move sideways & crush against each other and basket. Final touchdown was 65 metres beyond this point and stopped 35 metres further on. Surface wind 10-15 knots.	Thunder AX9-120 S2, G-BULK. Mini T-partition.	Given, briefed for fast landing.	1 crew, 6 passengers: 1 passenger sustained fractured pelvis.
3 May 1993	Basket was correctly orientated. The grass landing area sloped gently upwards in direction of travel. During touch down basket toppled and dragged for 24 feet. Elderly passenger lost grip. Surface wind 7 knots.	Cameron A-105, G-BRZB. Open.	Given	1 crew, 5 passengers: 1 elderly passenger broke arm.
23 Jun 1993	Balloon landed firmly on field of grass, then dragged basket for 10 metres before it tipped onto its side. Surface wind 6 knots.	Cameron A-180, G-BTYE. Double T-partition.	Unknown	1 crew, 8 passengers: 1 elderly passenger suffered a cracked tibia, but had weak bones.
5 Oct 1993	Balloon encountered cumulo nimbus cloud. Balloon landed heavily. Pilot and 1 crewmember thrown out of basket. Balloon with 2 passengers left lifted again flew short distance then struck power cables separating envelope from basket. Surface wind > 25 knots	Cameron N-90, G-CONC. Open.	Unknown	2 crew, 2 passengers: 1 serious and 3 minor injuries.

Table 1 UK hot-air balloon accidents caused by hard landings between January 1993 and January 2003 (Continued).

Date	Landing Scenario	Balloon & Basket Type	Landing Positions	Passengers Injuries
23 Oct 1993	Landing made difficult by adjacent hills. Before touchdown the basket tipped a treetop twice. On touch down, basket tipped over and dragged for short distance. An elderly passenger knocked into another passenger. Surface wind 10-15 knots, gusting to 25 knots.	Cameron A-210, G-BTCK. Single T-partition.	Given, but injured passenger was prevented from sitting correctly by another passenger who was incorrectly positioned in that section.	1 crew, 10 passengers: 1 elderly passenger broke arm.
29 Apr 1994	Landing on large field on top of a ridge. Initial touchdown was firm and basked dragged for 50 yards, lifted off again briefly and after another landing basket dragged 30 yards. Other passenger landed on elderly man. Surface wind 8 knots gusting to 15 knots.	Cameron O-120, G-BTUU. Non-partitioned.	Given, a.o. were told to bend knees. Elderly passenger was at front and would have taken the weight of other passenger during ground drag.	1 crew, 5 passengers: 1 elderly passenger broke leg, 2 passengers sustained minor injuries.
23 Jul 1994	Envelope deflated rapidly. On touchdown, the basket turned over and 2 elderly passengers were thrown out. This caused the balloon to become airborne again and made second heavy landing. Surface wind increase from 12 to 15 knots.	Cameron A-120, G-SKYP. Single partition.	Given, also warning for fast landing, a.o. to hold on tight. 2 elderly passengers rear. Before second landing 1 passenger not in correct landing position.	1 crew, 5 passengers: 2 elderly passengers sustained minor injuries, passenger in incorrect landing position broke ankle.
5 Aug 1994	Two impacts on the ground, than a short drag. Landing positive at about 250 ft/min. Surface wind 6-8 knots.	Colt 120A, G-BOJO. Unknown.	Given.	1 crew, 4 passengers: 1 passenger sustained fractured ankle.
10 Oct 1994	After first touchdown, which was normal, balloon rose again to 10 feet. At subsequent also normal touchdown the basket initially stayed upright, but wind on envelope caused basket to topple onto its side. Surface wind forecast 10 knots.	Thunder and Colt 240A, G-BVJL. Single T-partition.	Given, facing backward.	1 crew, 10 passengers: 1 passenger broke left tibia.
22 Mar 1995	Basket struck hedge and than dragged for 150 yards. Surface wind 10 knots gusting to 16 knots.	Cameron N-90, G-PRIT. Open.	Given, facing backward and hold onto rope handles.	1 crew, 3 passengers: 1 passenger broke rib, 1 sustained a minor injury.
16 Jul 1995	Pilot made normal approach to field with long grass. After touchdown balloon dragged 50 yards coming to rest against far side of wide ditch at right angles to balloon's path and had not been seen due to long grass. Surface wind 10 knots.	Thunder AX9-120, G-BUAT. Mini T-partition.	Given, instruction according to pilots normal practice.	1 crew, 4 passengers: 1 passenger sustained broken bone in foot.

Table 1 UK hot-air balloon accidents caused by hard landings between January 1993 and January 2003 (Continued).

Date	Landing Scenario	Balloon & Basket Type	Landing Positions	Passengers Injuries
27 Jul 1995	Land in cut crop field. Approach was too low causing firm contact with hedge. Balloon went up again and made hard impact on ground. Local surface wind 16-18 knots.	Cameron O-84, G-BOWU. Open.	Unknown	1 passenger sustained broken limb
17 Dec 1995	Positive landing with minimal drag. Surface wind 4 knots.	Cameron O-105. G-BSNZ Partitioned.	Unknown	1 crew, 5 passengers: 1 passenger sustained fractured ankle
28 Apr 1996	Increase of wind to 15 knots and light turbulence. Touchdown was firm and tipped over. Basket was dragged for 150 metres coming to rest with open end of basket against a bramble hedge.	Thunder and Colt 180 A, G-BSUU. Single T-partition.	Given.	1 crew, 9 passengers (incl. 2 children): passenger sustained cut hand and bang to the head.
6 Jun 1996	Basket landed on second impact on the ground. Injured passenger had straightened his leg before the second landing. Surface wind 6 knots.	Cameron A-180, G-BUII. Double T-partition.	Given.	10 perpons on board: 1 elderly passenger sustained minor knee injury.
14 Jul 1996	Basket toppled following a firm landing.	Cameron A-250, G-BUXR. Partitioned.	Given, but the injured passenger failed to adopt pre-briefed landing position.	1 crew, 13 passengers 1 passenger sustained broken ankle, no injuries to other 12 passengers.
31 Mar 1997	Balloon landed with a great rate of descent. Basket landed with the corner first with too great descent rate, by which it was rotated. 6 of 7 rear passengers were thrown from the basket during the rotation. The basket dragged for 170 metres. Surface wind forecast was gusting to 25 knots.	Sky 220-24, G-SPEL. Double T-partition.	Given, hold onto rope handles and bend knees.	2 crew, 11 passengers (incl. 1 child): 1 passenger seriously injured, 11 had minor injuries.
31 Mar 1997	Passenger's foot became trapped behind fuel cylinder and broke when balloon landed heavily. Balloon contacted hedge during landing due to fog and increase of wind speed.	Cameron V-77, G-BWKV. Unknown	Unknown	1 passenger sustained broken lower leg.
19 Jul 1997	Hard landing due to fuel exhaustion. Balloon developed high descent rate and bounced after touchdown up to 20 feet before second hit with ground. Pilot warned for hard landing.	Sky 220-24, G-SPEL. Double T-partition.	Instructed to adopt position with backs to landing direction, bend knees and hold onto ropes on inside of basket and remain within basket after landing.	1 crew, 12 passengers: 1 passenger broke leg, 1 passenger had minor back injuries, 4 passengers had sprained ankles.

Table 1 UK hot-air balloon accidents caused by hard landings between January 1993 and January 2003 (Continued).

Date	Landing Scenario	Balloon & Basket Type	Landing Positions	Passengers Injuries
14 Feb 1998	Balloon encountered turbulence and made heavy landing. Surface wind 15-20 knots.	Colt 90A, G-OBBC. Open.	Passengers were briefed for a hard landing.	1 crew, 2 passengers: pilot suffered broken leg.
20 May 1998	Basket made hard landing due to deteriorating weather	Cameron N-90 G-TEEZ	Unknown	1 serious injury
20 May 1998	Turbulence caused a hard and fast landing, which dragged the basket for 200 yards. First contact on the ground probably caused broken wrist. Ground speed was 19 knots.	Cameron O-120, G-BWKD. Mini T-partition.	Briefed for hard and prolonged landing.	1 crew, 5 passengers: 1 passenger broke wrist, 4 passengers sustained bruises and grazes
11 Aug 1998	Heavy landing by uncontrollable rate of descent. Balloon bounced and subsequent landing was normal. Surface wind forecast 7-10 knots.	LBL 180A, G-EVNT. Single T-partition.	Unknown	1 pilot and 8 passengers: 1 elderly passenger sustained 2 broken legs.
18 Sep 1998	Steep descent and contact withh ground. Flight continued. Basket struck trees during landing.	LBL 310A, G-SIZE. Double T-partition.	Unknown	1 passenger sustained minor injuries.
18 Sep 1998	Balloon dragged on landing. Basket struck fence and rolled over. Wind speed increased significantly.	LBL 210A, G-BXNX. Unknown.	Unknown	9 passengers: 1 passenger sustained minor injury.
27 Jul 1999	Basket correctly aligned with ground before landing. There was very little descent, but a mild jolt when basket first contacted surface. The basket tipped over and was dragged for a few metres. Light surface wind 5 knots.	LBL 210A, G-BVML. Single T-partition.	Given, a.o. to bend knees. Inured passenger may have omitted to bend through knees.	1 pilot, 11 passengers: 1 elderly passenger suffered minor knee injuries.
16 Jun 2000	Basket struck hedge during landing.	Cameron O-120, G-BTEE. Mini T-partition.	Given, the injured passenger may have lost grip to the rope handle.	1 crew, 5 passengers: 1 passenger sustained a broken bone in arm.
30 Dec 2000	Balloon encountered turbulence over a hill and contacted a tree, causing the basket to swing. Landing was made on frozen ground and basket slid into a barbed wire fence.	Thunder & Colt AX8-90, G-BSTY. Open.	Unknown	1 crew, 2 passengers: 1 passenger sustained fractured ankle.
16 Aug 2002	Basket toppled on landing after contacting some ruts in the earth. 1 pilot and 3 passengers on board. Surface wind speed increased from 5-7 to 10-12 knots.	Thunder AX8-105, G-BPZZ. Open.	Given	1 elderly passenger sustained fractured ankle.
8 Sep 2002	Unknown.	LBL 90A, G-JEMY. Open.	Unknown	1 passenger sustained broken ankle.

Appendix B Landing Tests

The acceleration measurements are shown in Figure 1 to Figure 16. The positive x-direction of the acceleration is perpendicular to the front basket wall in the travel direction. The positive y-direction of the acceleration is parallel to the front basket wall pointing in the right direction. The positive z-direction of the acceleration is pointing in the upward direction.

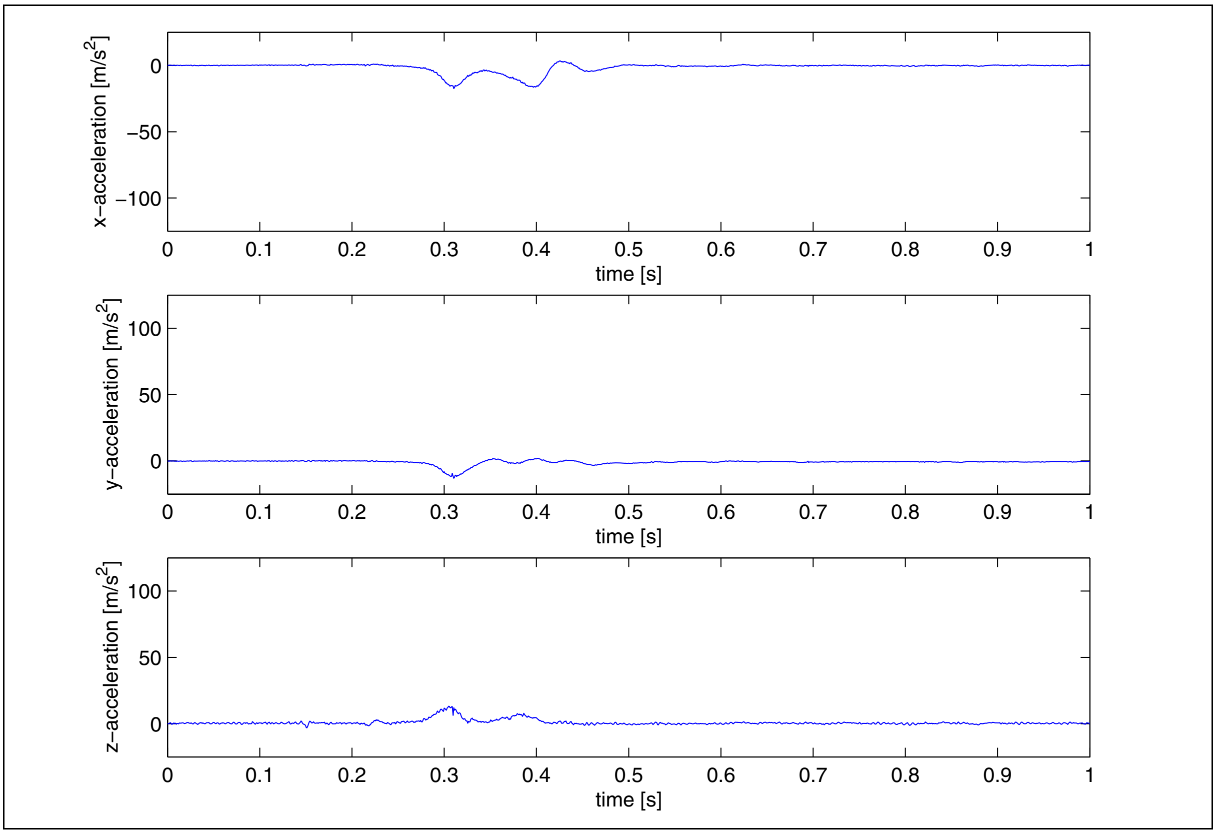

Figure 1 Test 1. Normal landing: velocity 2.5 knots, descent rate 120 ft/min.

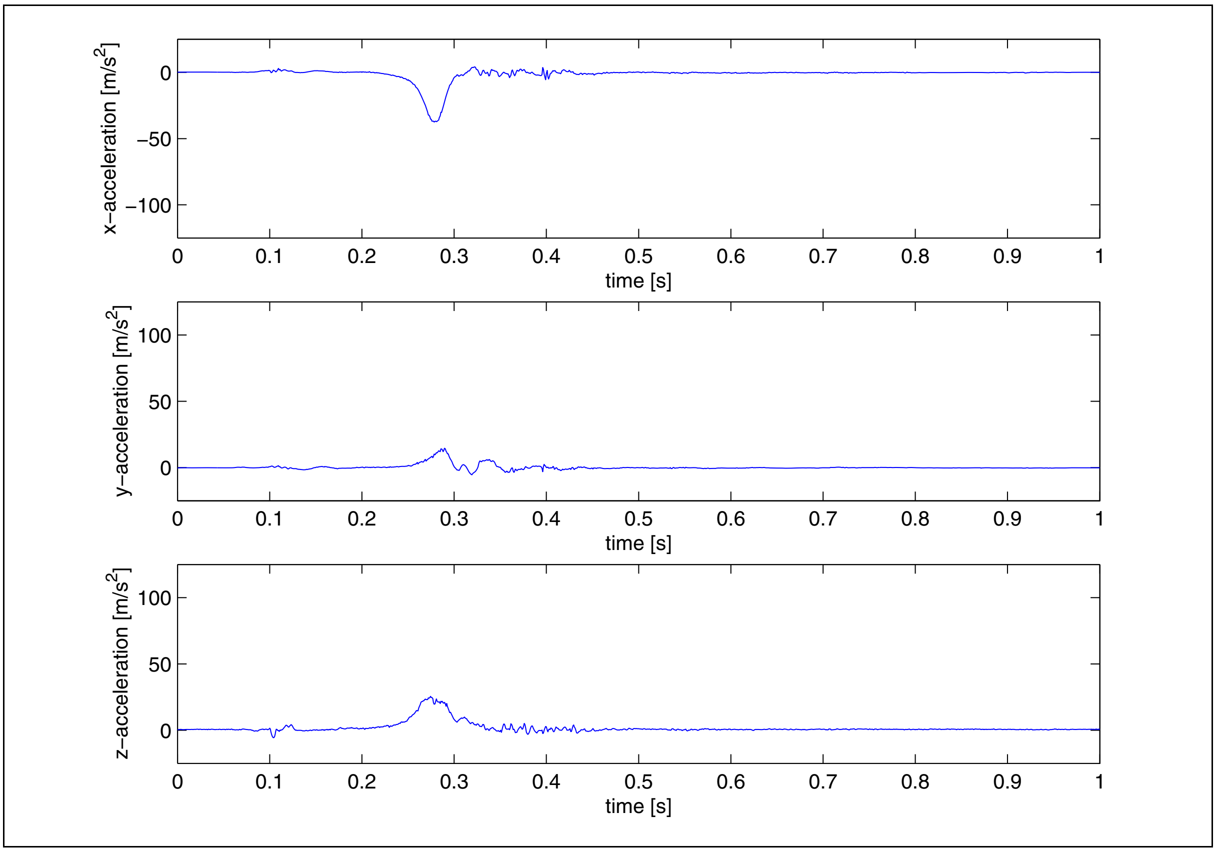

Figure 2 Test 2. Normal landing: velocity 2 knots, descent rate 160 ft/min.

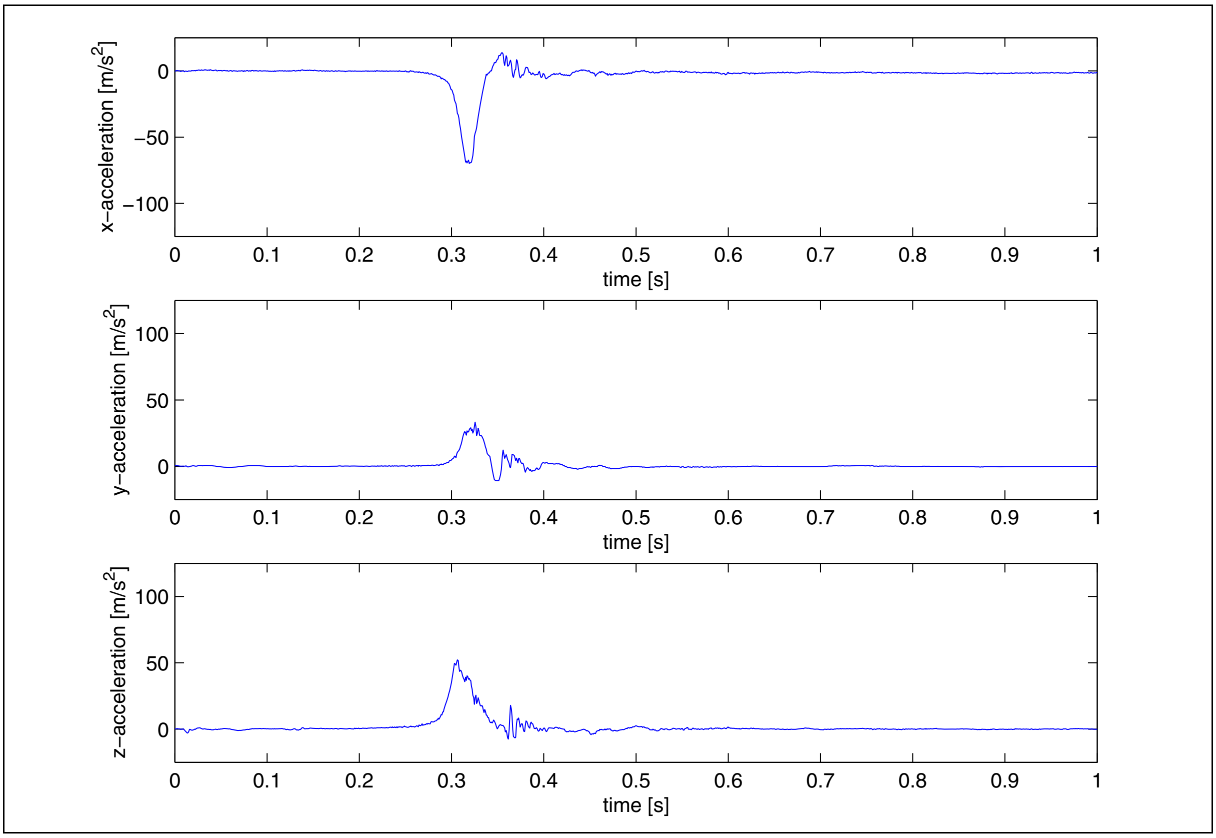

Figure 3 Test 3. Heavy landing: velocity 2.5-3 knots, descent rate 320 ft/min.

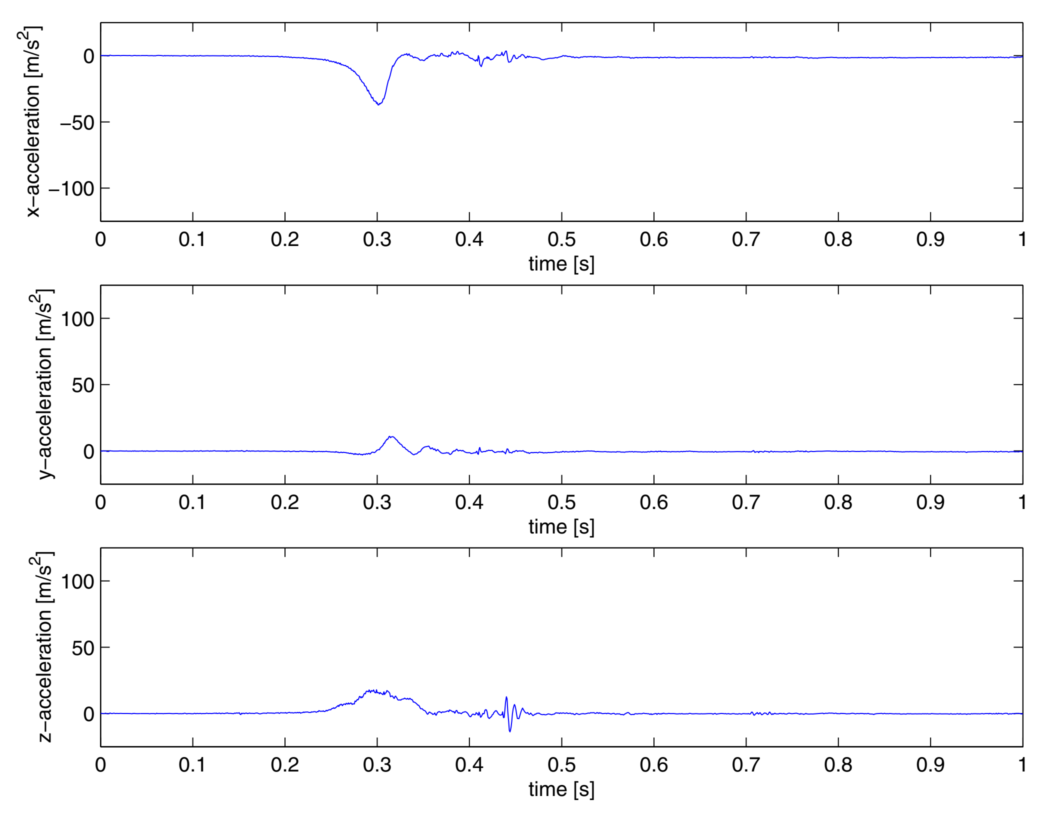

Figure 4 Test 4. Heavy landing: velocity 2.8 knots, descent rate 240 ft/min.

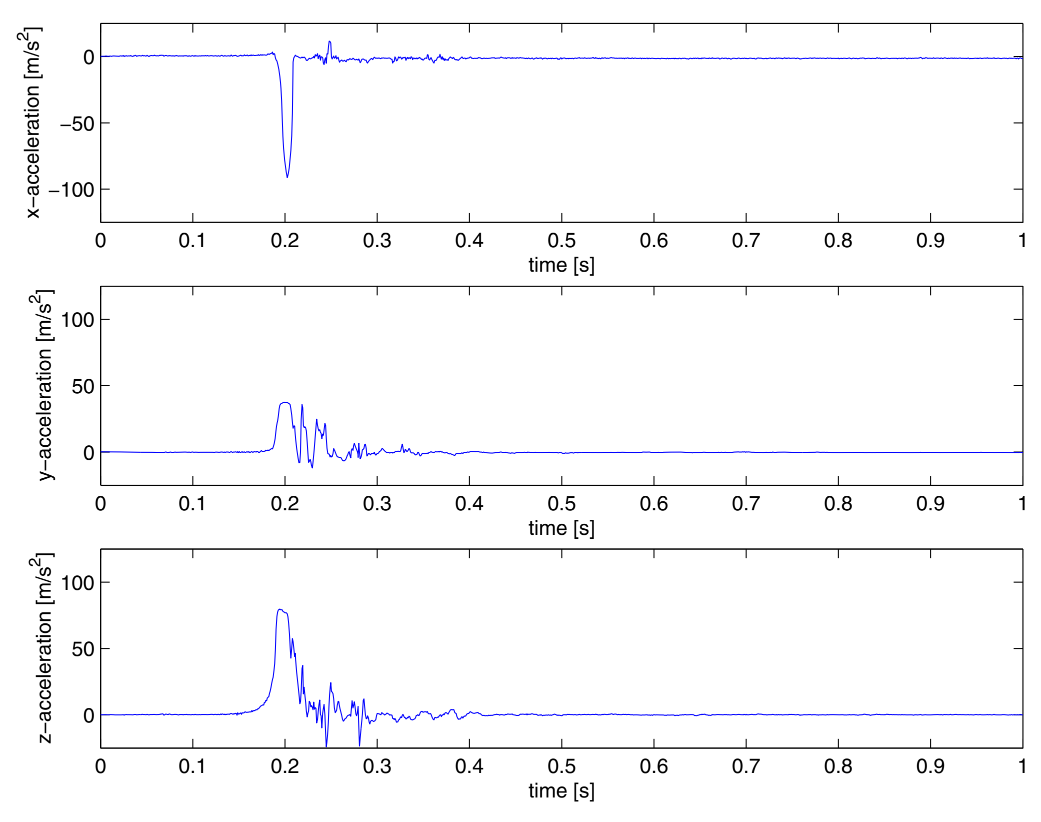

Figure 5 Test 5. Heavy landing: velocity 1.8-2 knots, descent rate 560 ft/min. The y- and z-acceleration were over the measuring range (result: round top).

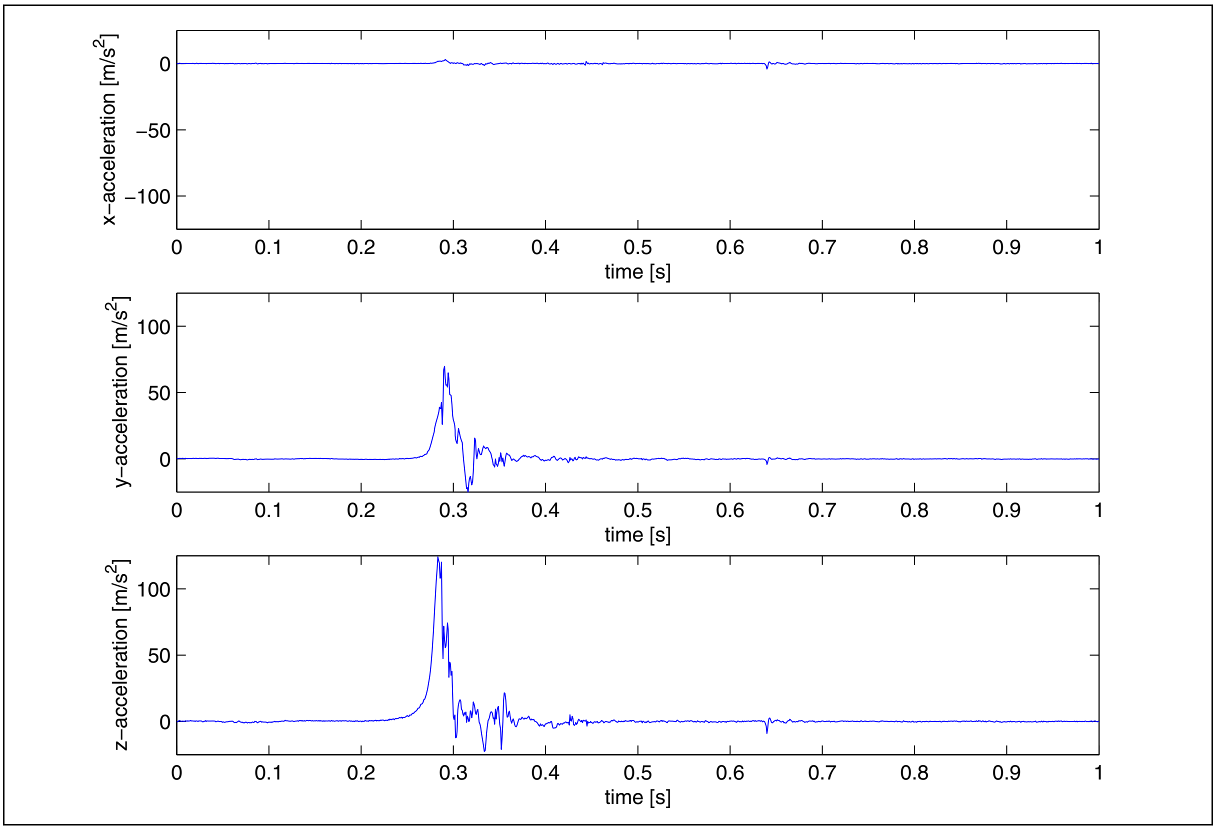

Figure 6 Test 6. Heavy landing: velocity 4 knots, descent rate 500 ft/min. The x-acceleration cable got under the cylinder and broke during this landing.

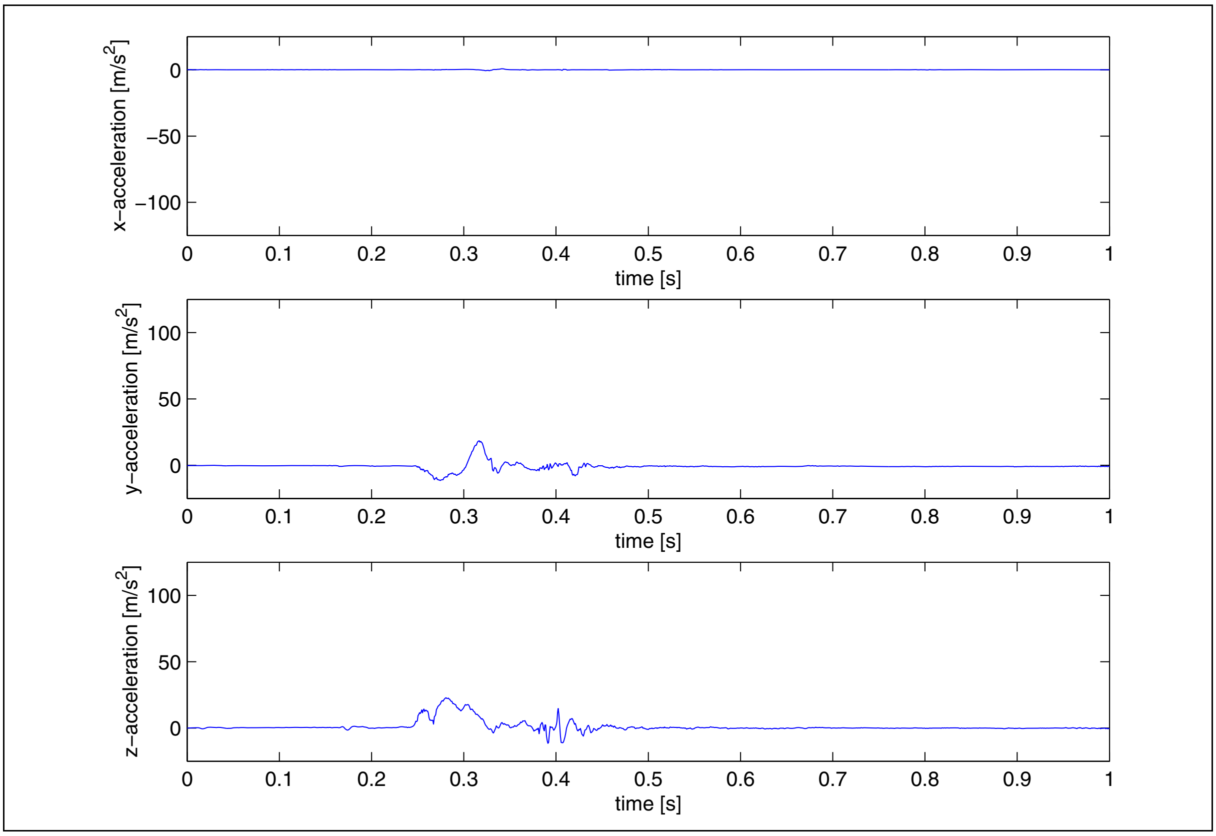

Figure 7 Test 7. Drag landing: velocity 4.1 knots, descent rate 200 ft/min.

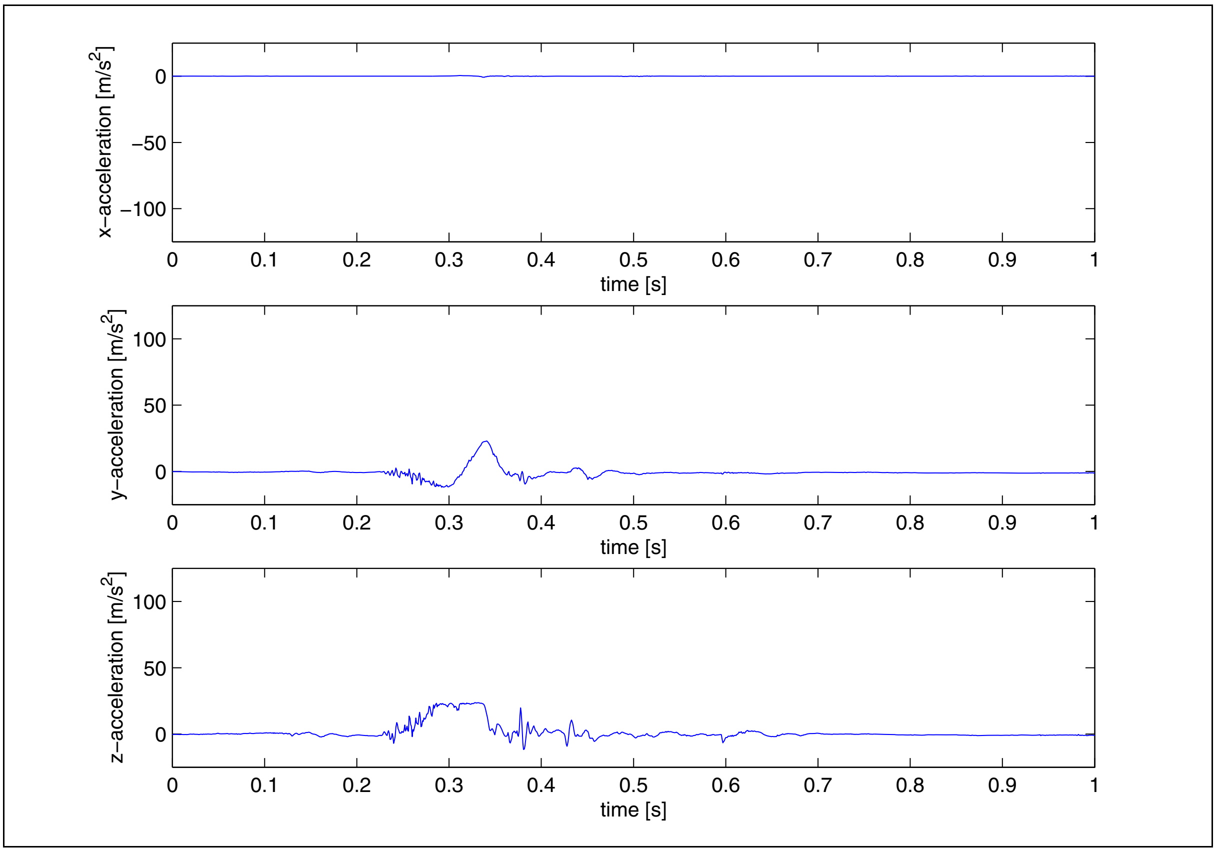

Figure 8 Test 8. Drag landing: velocity 4 knots, descent rate 300 ft/min.

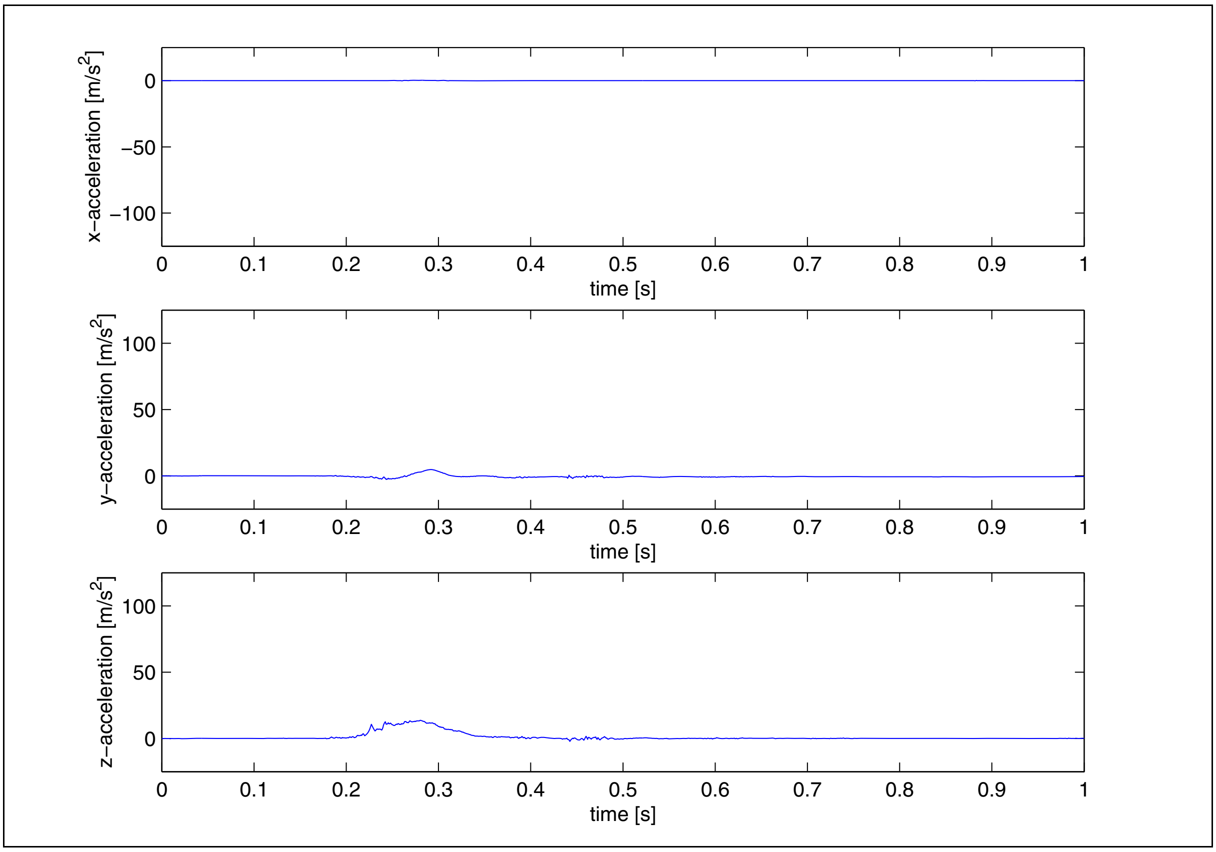

Figure 9 Test 9. Drag landing: velocity 3-3.5 knots, descent rate 140 ft/min.

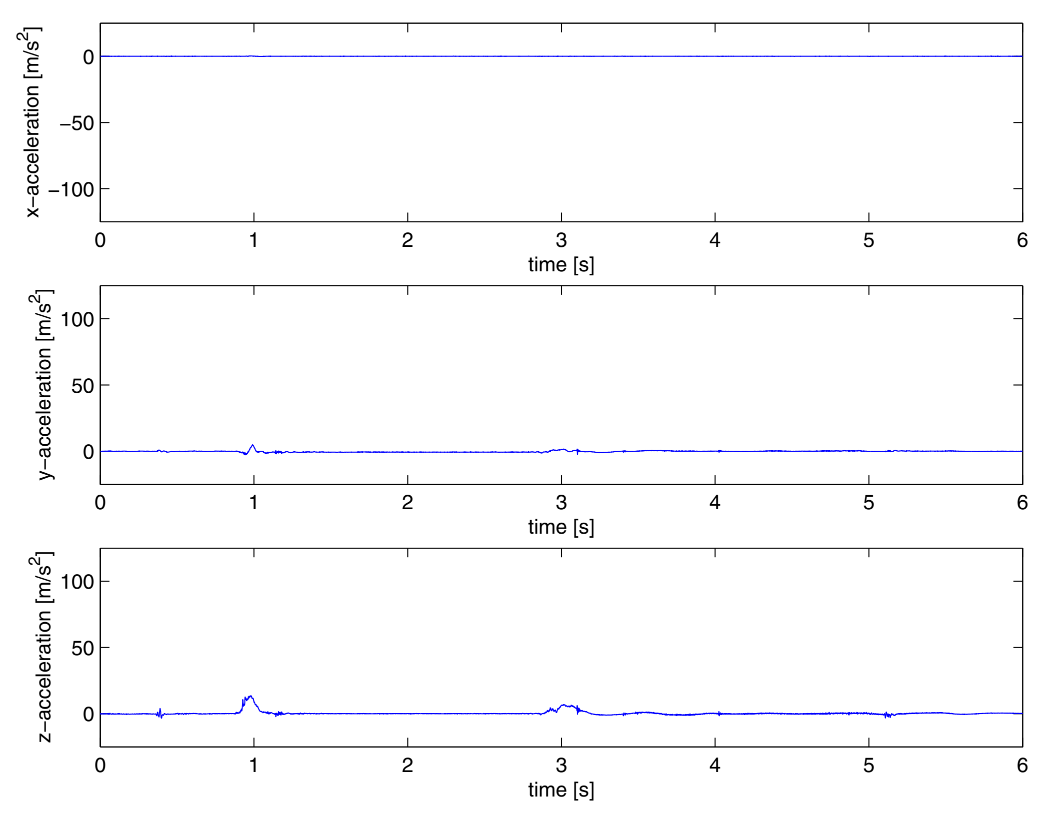

Figure 10 Test 9 over a longer time period in which a second touch down can be seen.

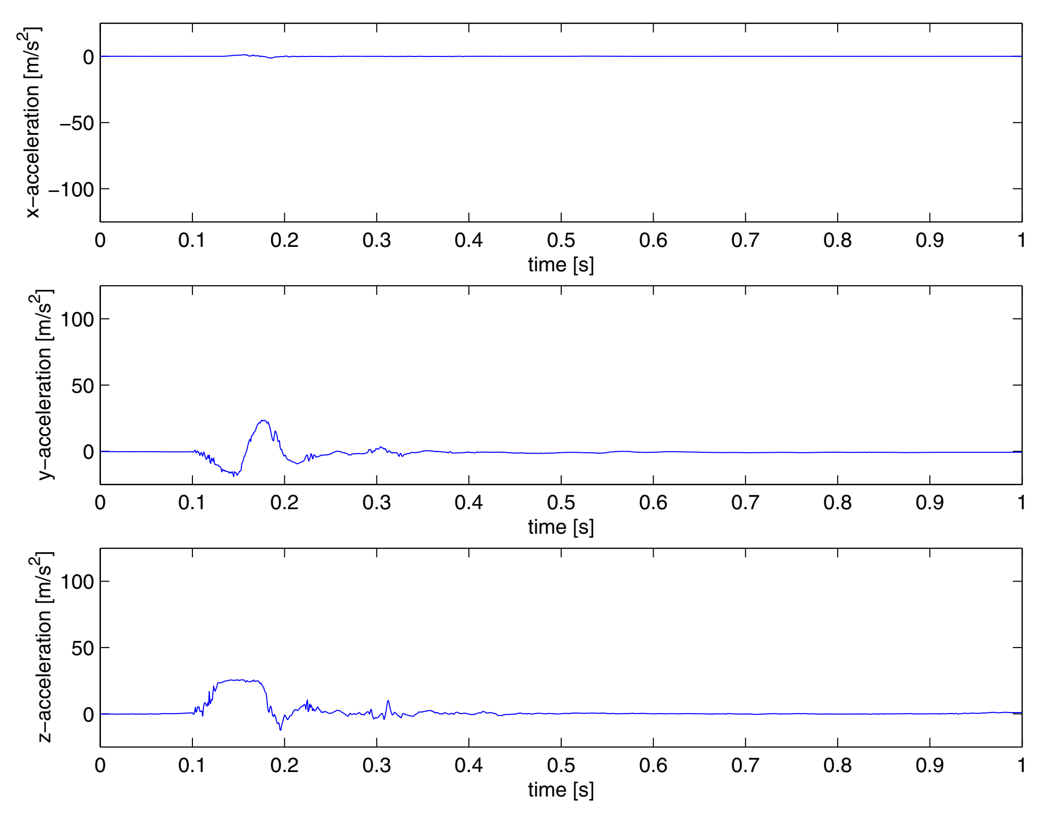

Figure 11 Test 10. Drag landing: velocity 3.5 knots, descent rate 400 ft/min. The z-acceleration was over the measuring range (result: round top).

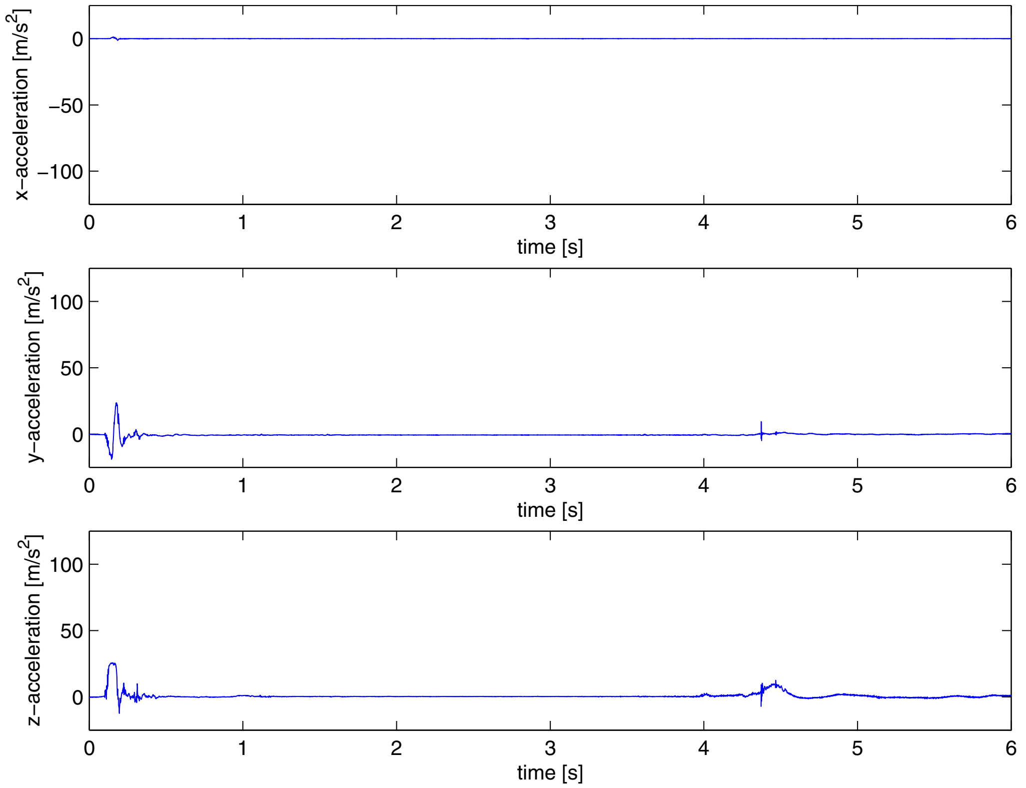

Figure 12 Test 10 over a longer time period in which a second touch down can be seen.

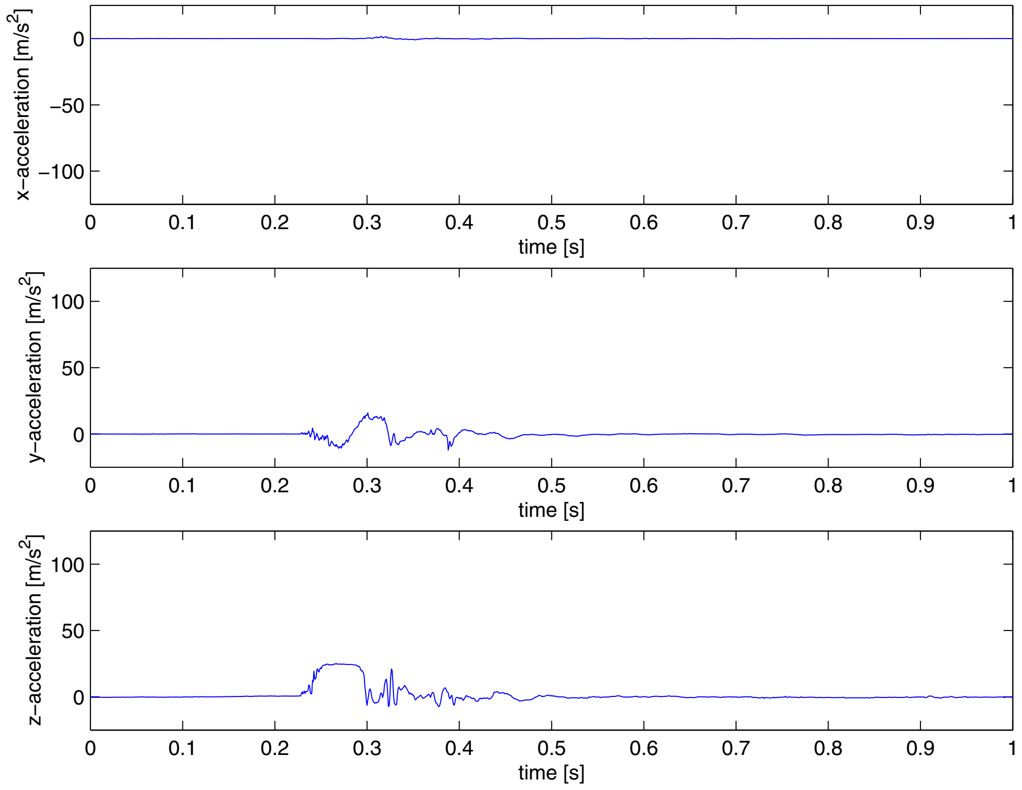

Figure 13 Test 11. Drag landing: velocity 3 knots, descent rate 420 ft/min. The z-acceleration was over the measuring range (result: round top).

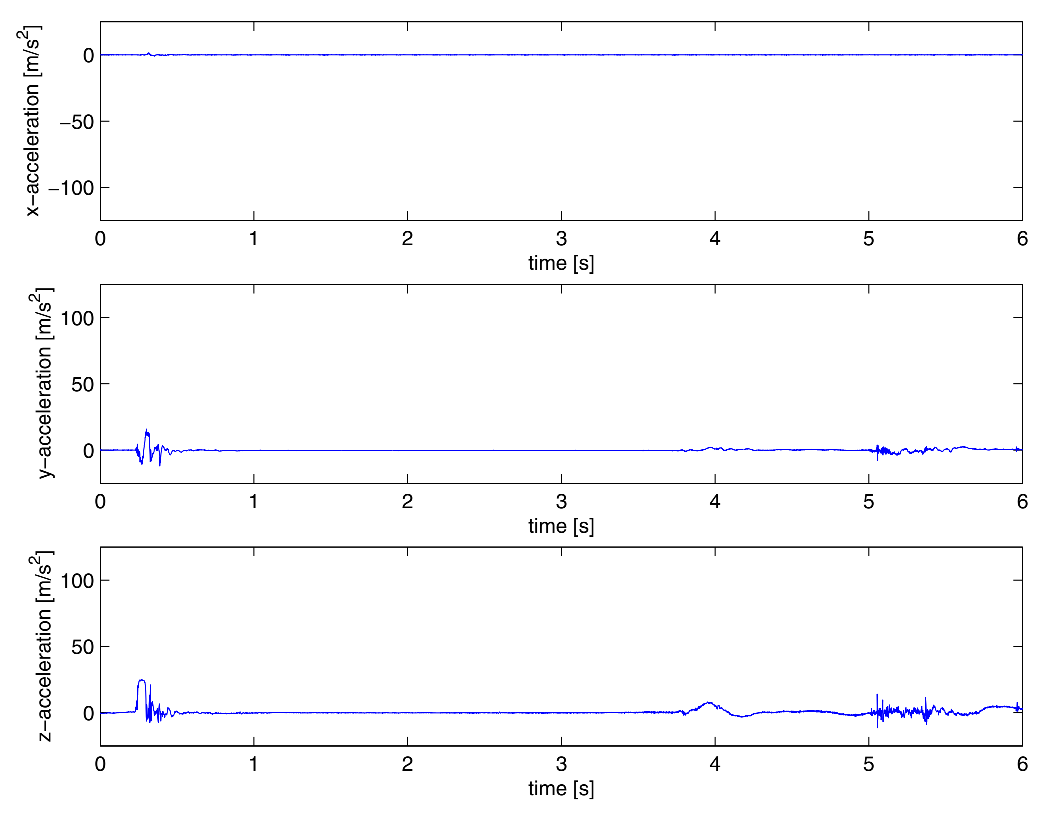

Figure 14 Test 11 over a longer time period in which a second and third touch down can be seen.

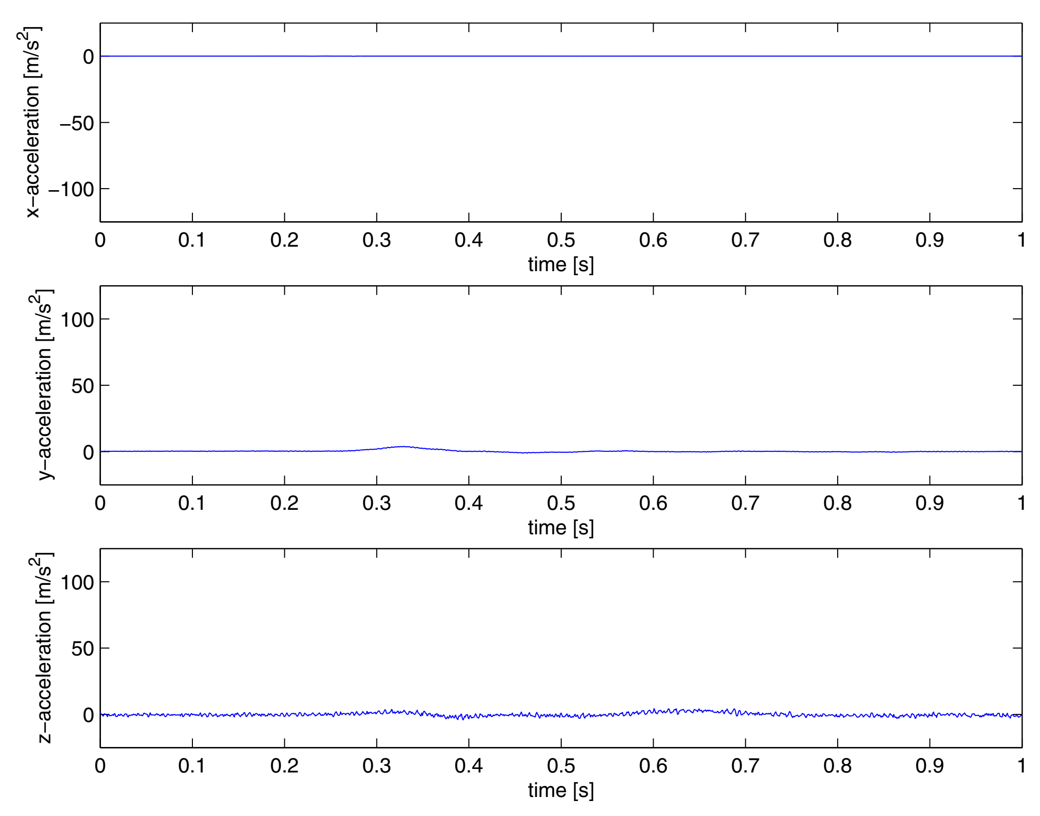

Figure 15 Test 12. Land with corner against ditch wall (basket front 45 degrees to ditch wall): velocity 3.7 knots, descent rate negligible.

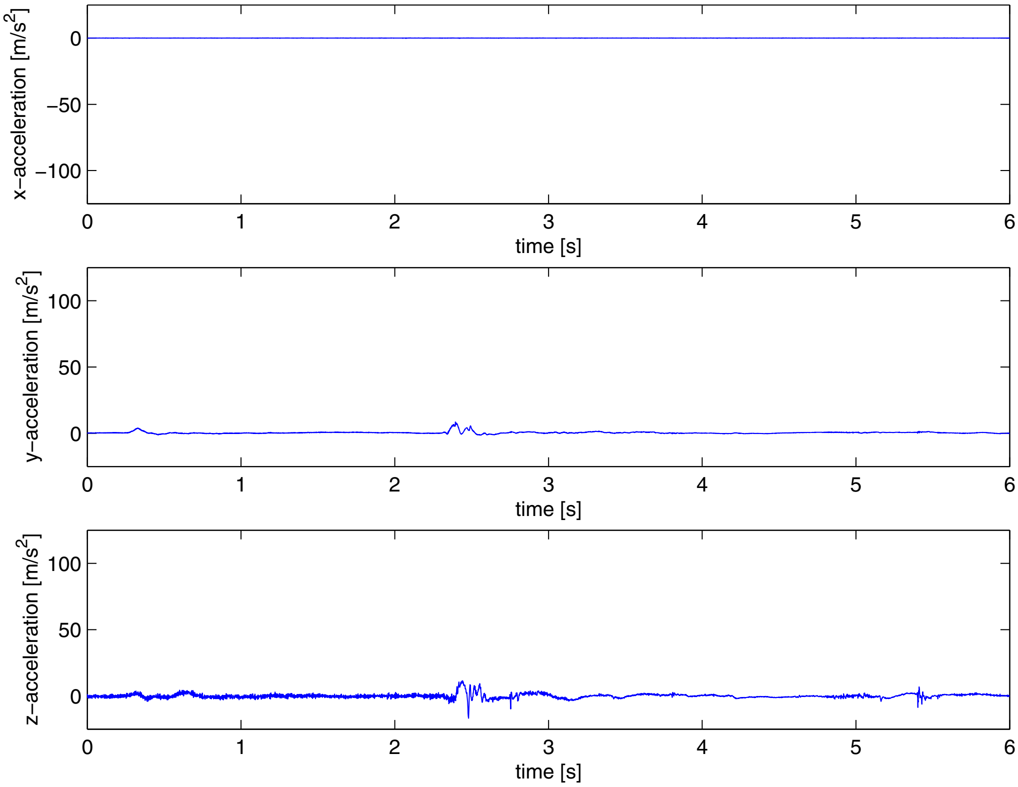

Figure 16 Test 12 over a longer period of time.

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Appendix C Simulation Results of Injury Criteria Values

Figures 1 to 8 show all the maximum injury criteria values resulting from all simulations described in Section 3. The black horizontal line in these bar diagrams show the injury tolerance limits of Section 3, Table 3. The calculated maximum injury criteria values are around the injury tolerance limits.

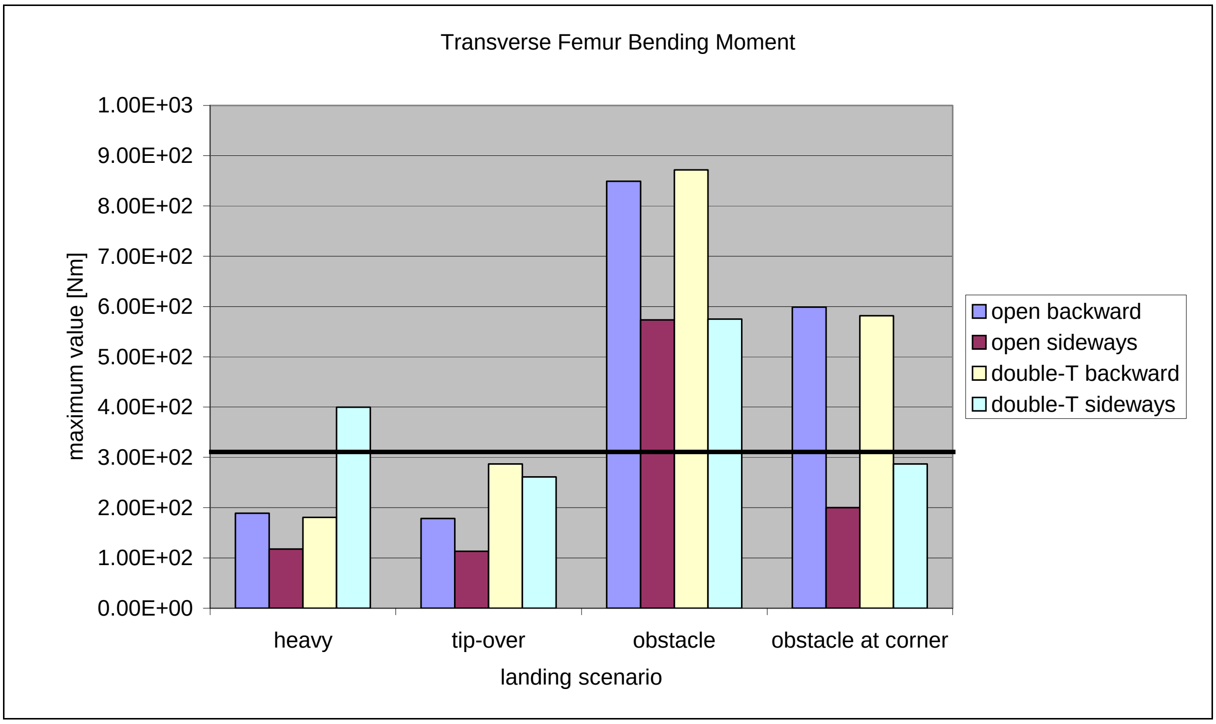

Figure 1 Maximum transverse femur bending moment resulting from the simulations.

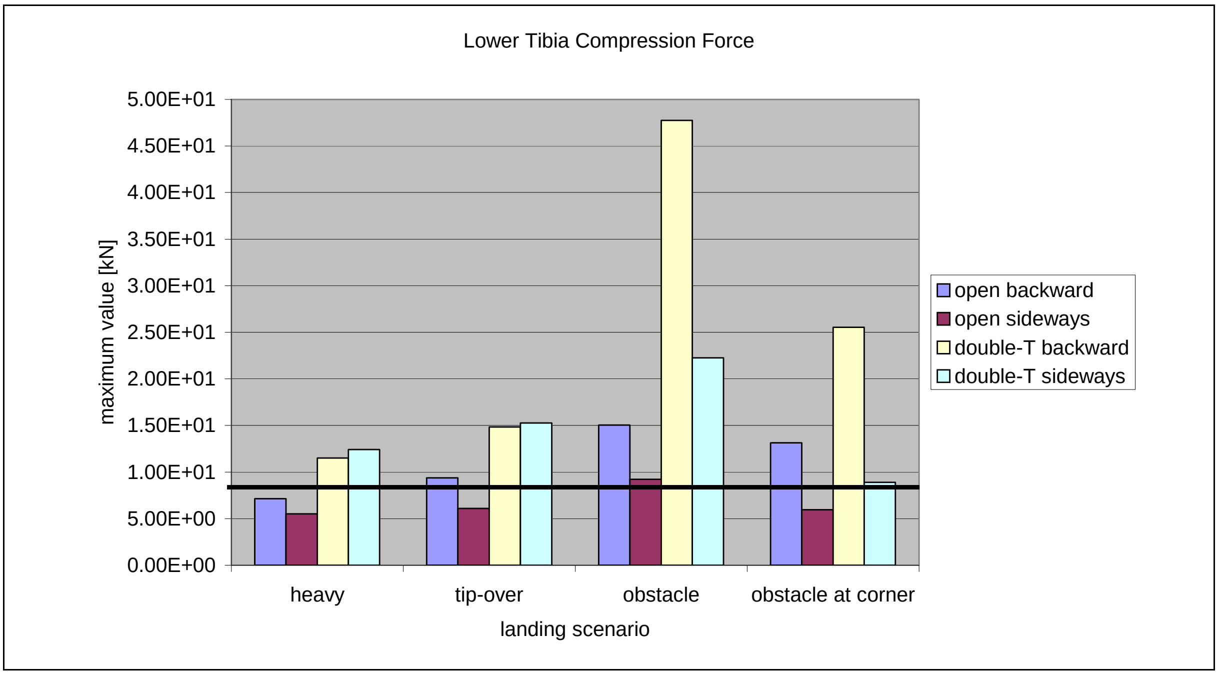

Figure 2 Maximum lower tibia compression force resulting from the simulations.

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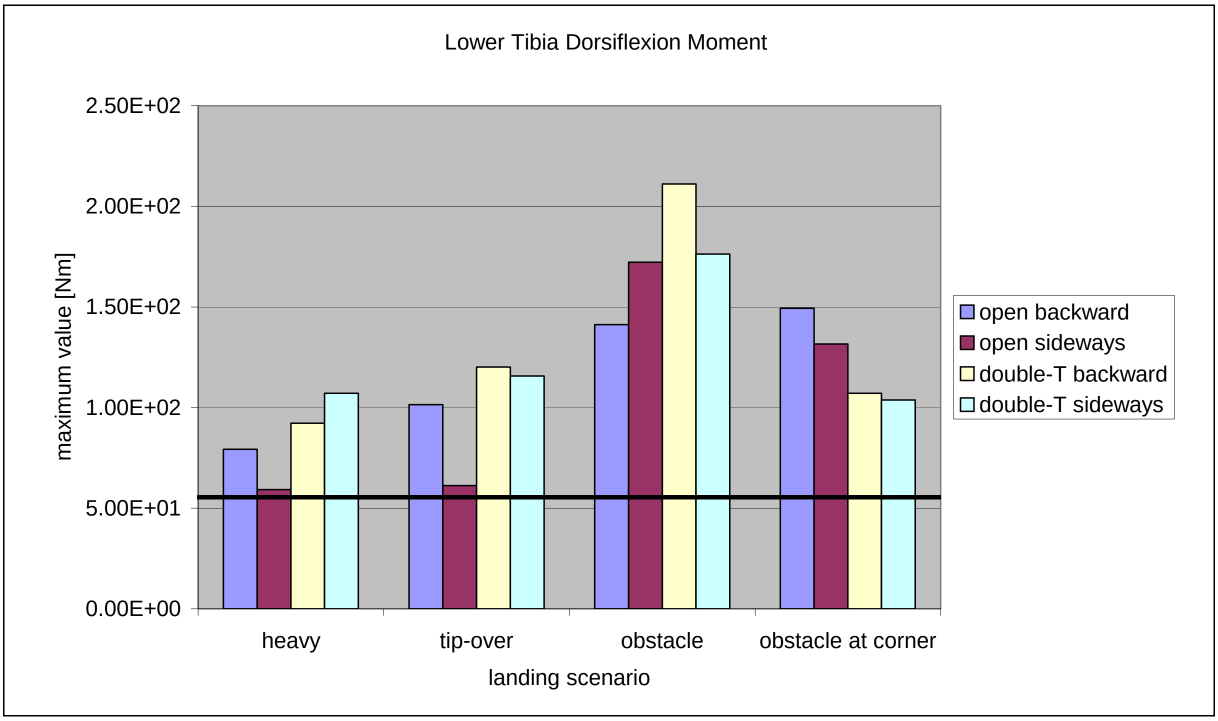

Figure 3 Maximum lower tibia dorsiflexion torque resulting from the simulations.

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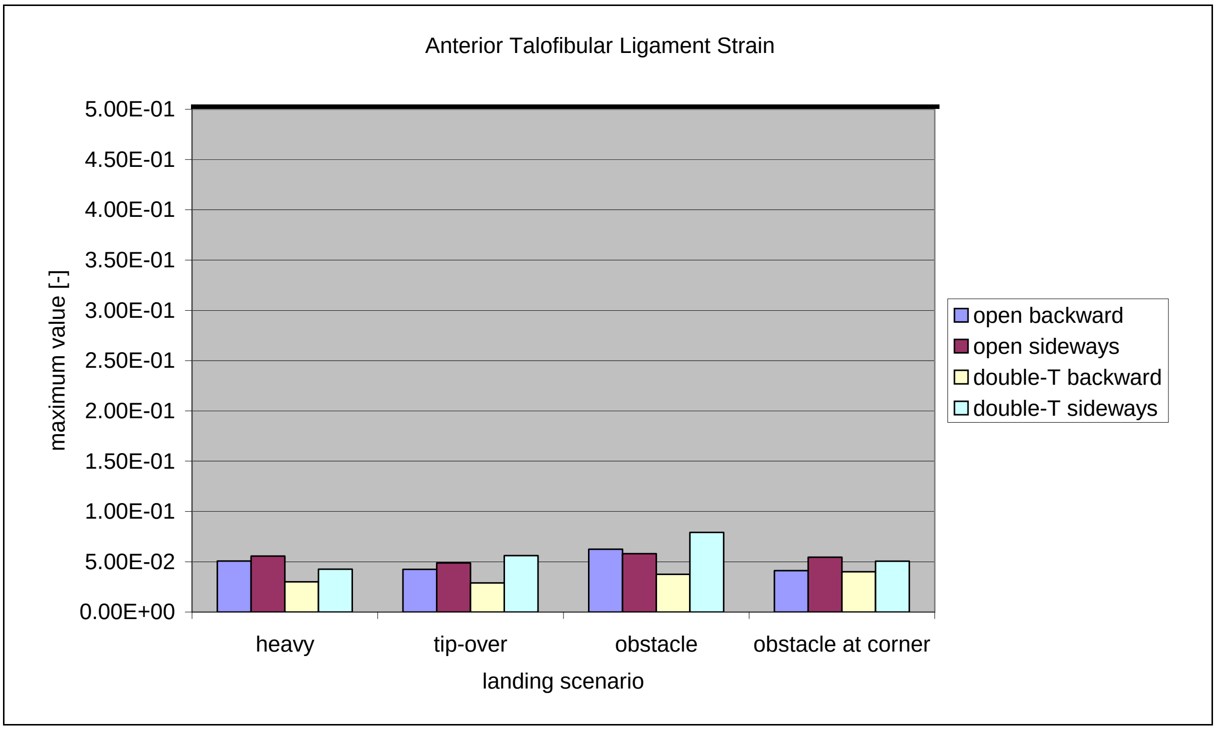

Figure 4 Maximum anterior talofibular ligament strain resulting from the simulations.

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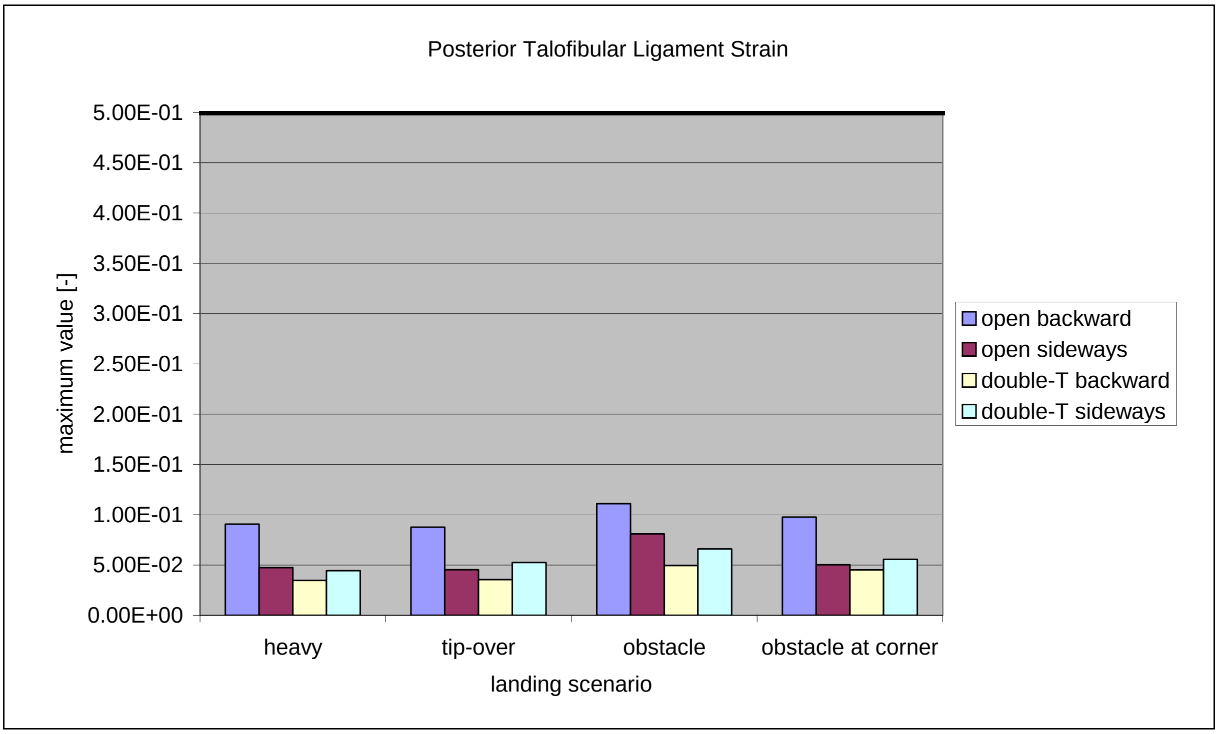

Figure 5 Maximum posterior talofibular ligament strain resulting from the simulations.

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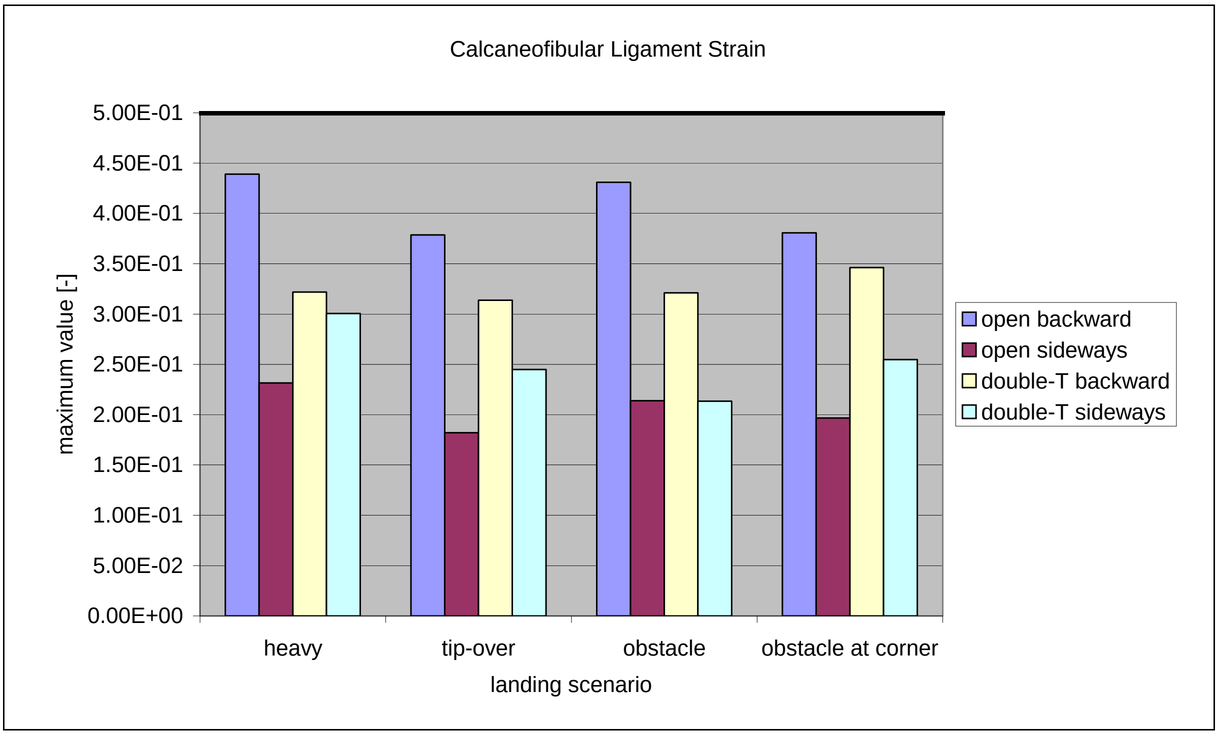

Figure 6 Maximum calcaneofibular ligament strain resulting from the simulations.

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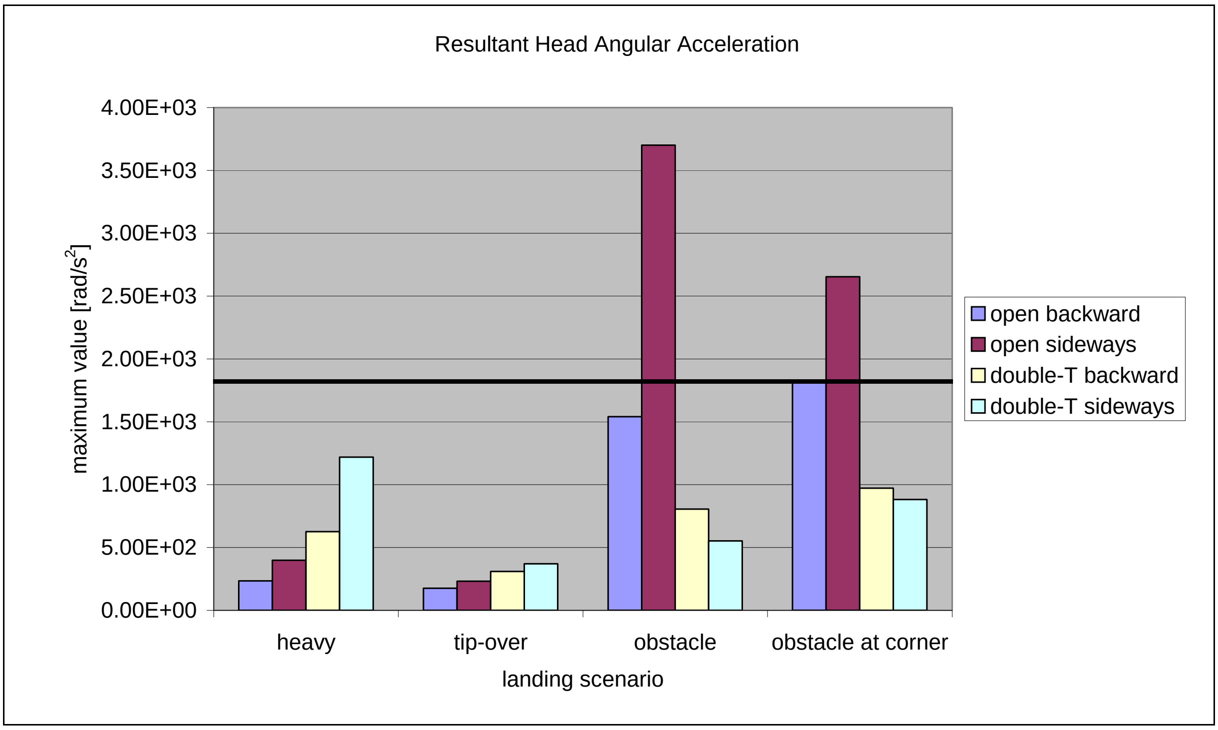

Figure 7 Maximum resultant head angular acceleration resulting from the simulations.

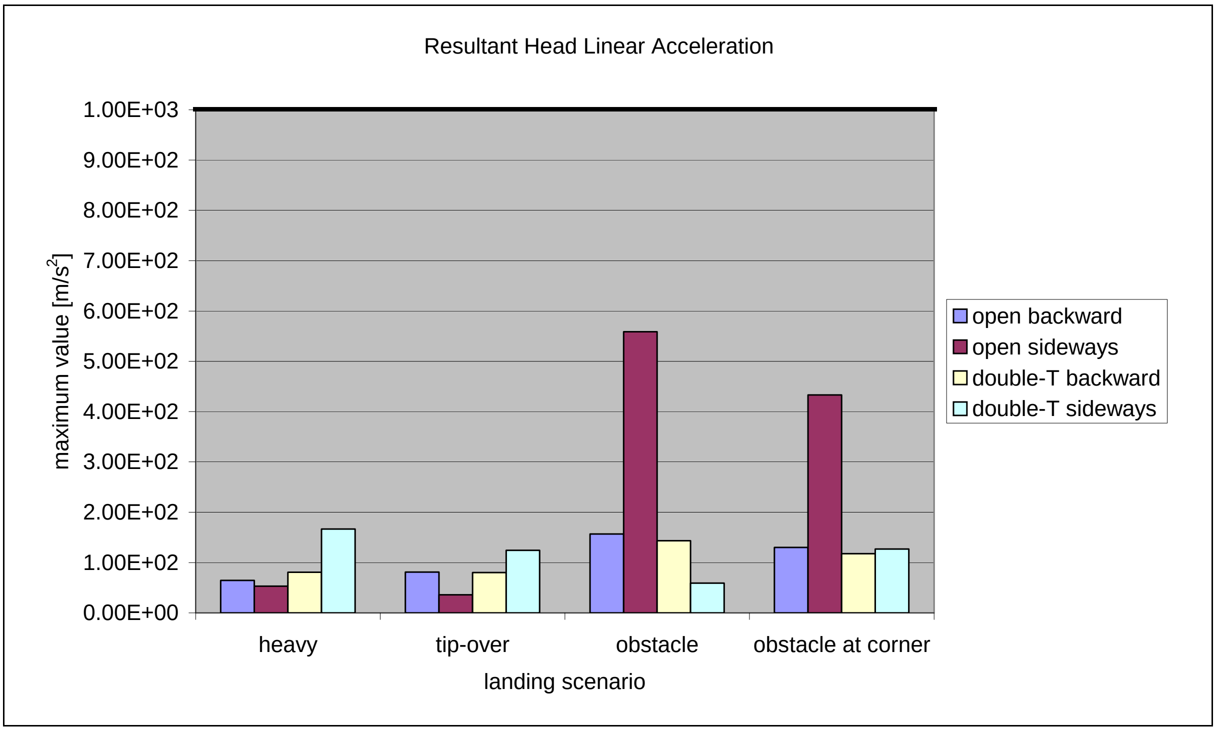

Figure 8 Maximum resultant head linear acceleration resulting from the simulations.

Appendix D Effect of Parameter Variation

A parameter variation on all the simulations described in Section 3 and Appendix C was performed. The leg muscle activity level was the parameter that was varied, it was increased by 50% for all the muscles that were activated, see Section 3, Table 2. Figures 1 to 8 show all the maximum injury criteria values resulting from all simulations in which the leg muscle activity was increased. The black horizontal line in these bar diagrams show the injury tolerance limits of Section 3, Table 3. The calculated maximum injury criteria values are around the injury tolerance levels, like for the original simulations.

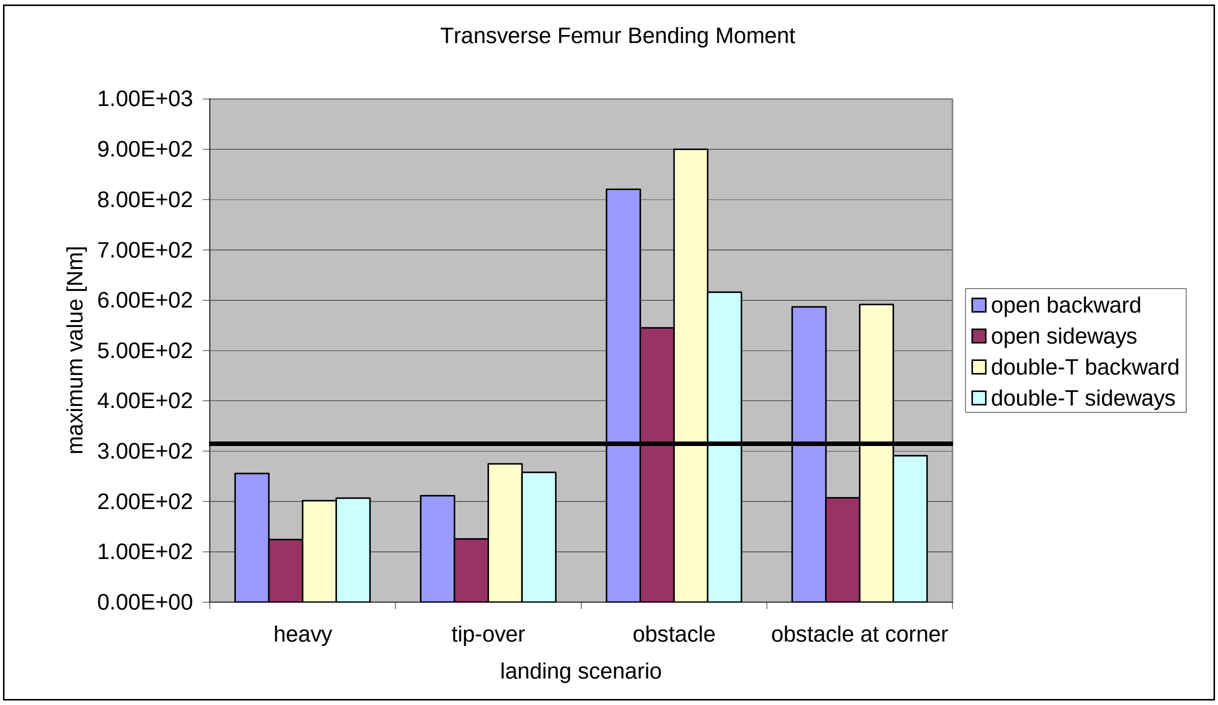

Figure 1 Maximum transverse femur bending moment resulting from the simulations.

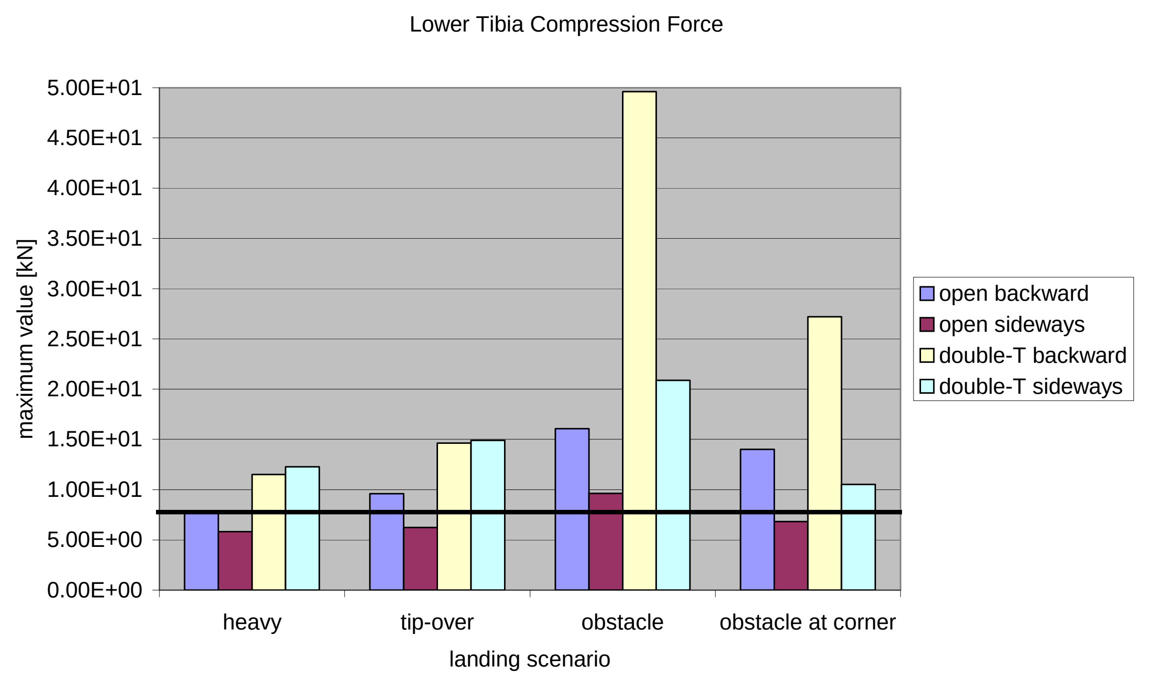

Figure 2 Maximum lower tibia compression force resulting from the simulations

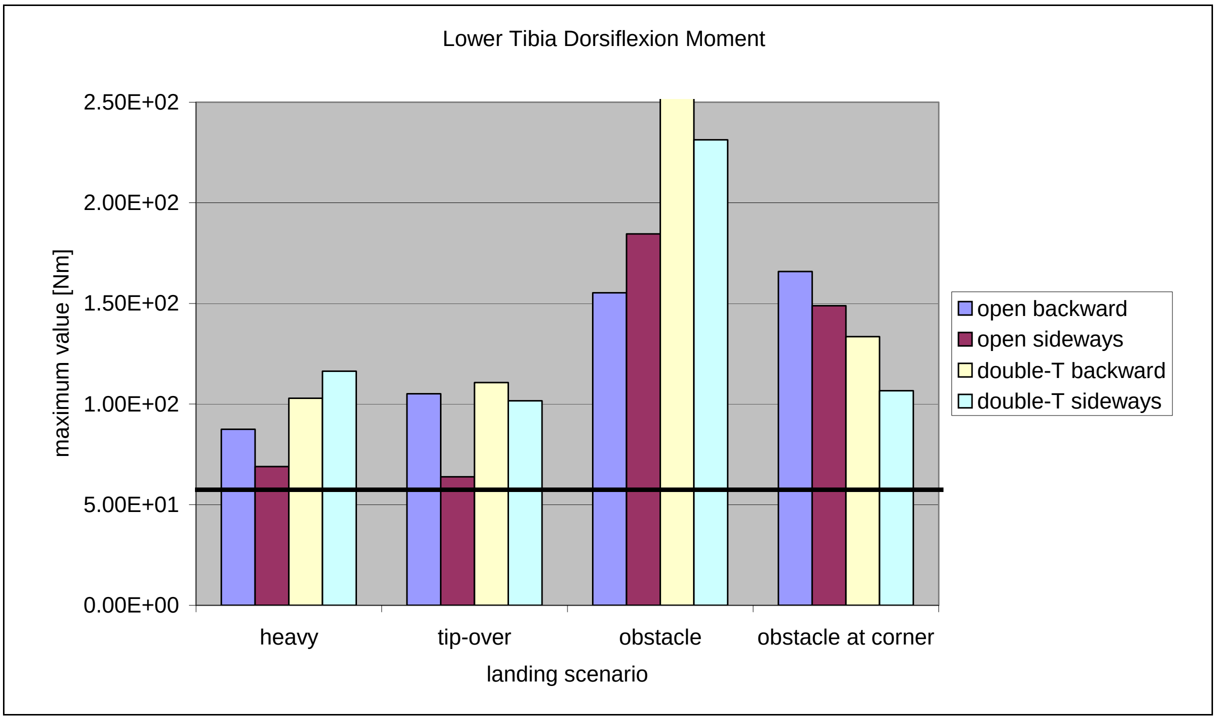

Figure 3 Maximum lower tibia dorsiflexion torque resulting from the simulations.

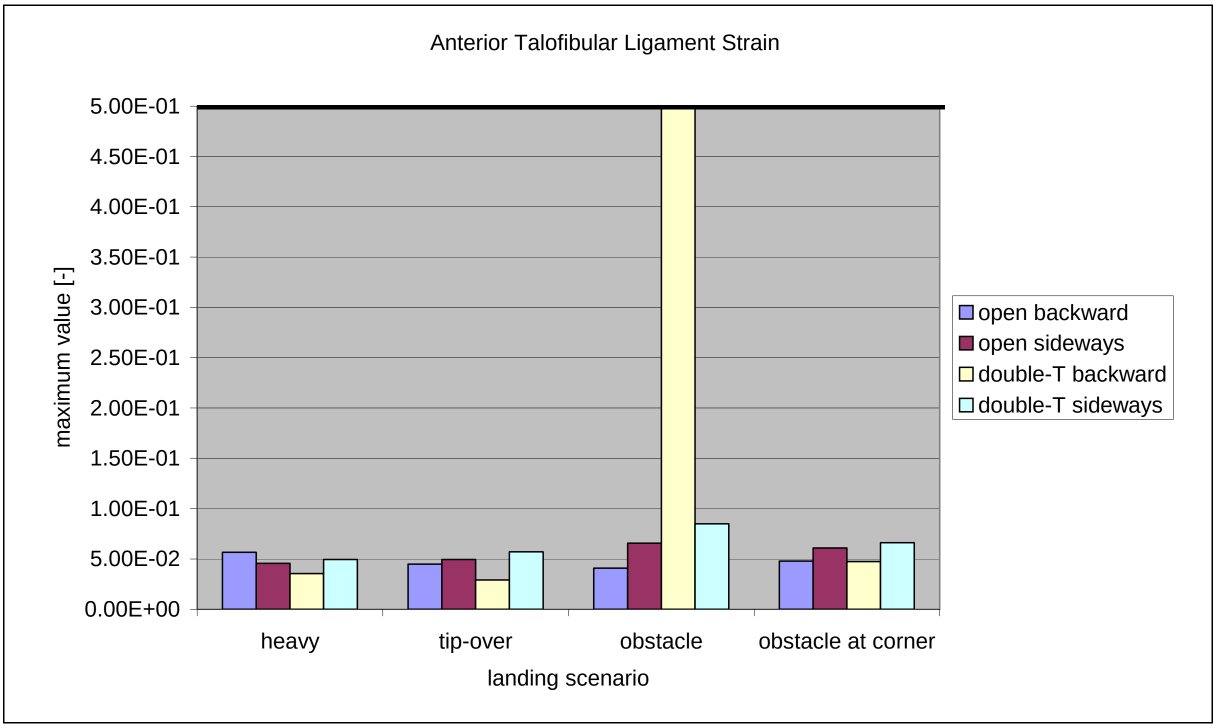

Figure 4 Maximum anterior talofibular ligament strain resulting from the simulations.

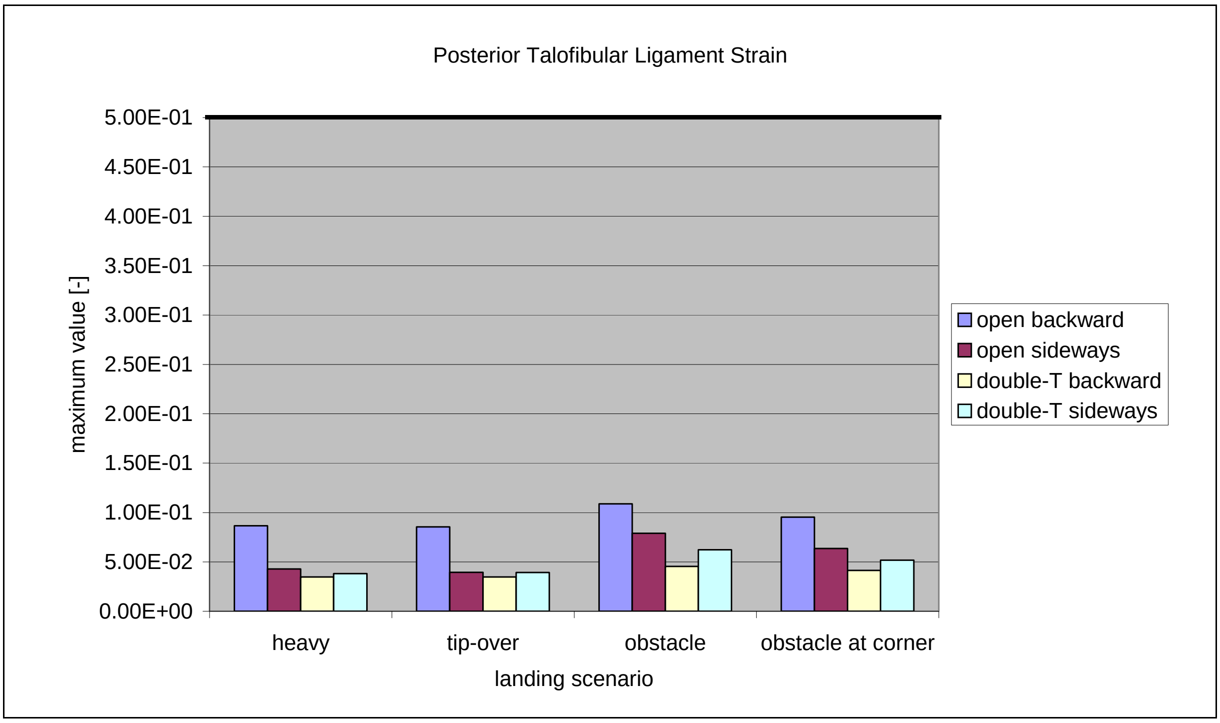

Figure 5 Maximum posterior talofibular ligament strain resulting from the simulations.

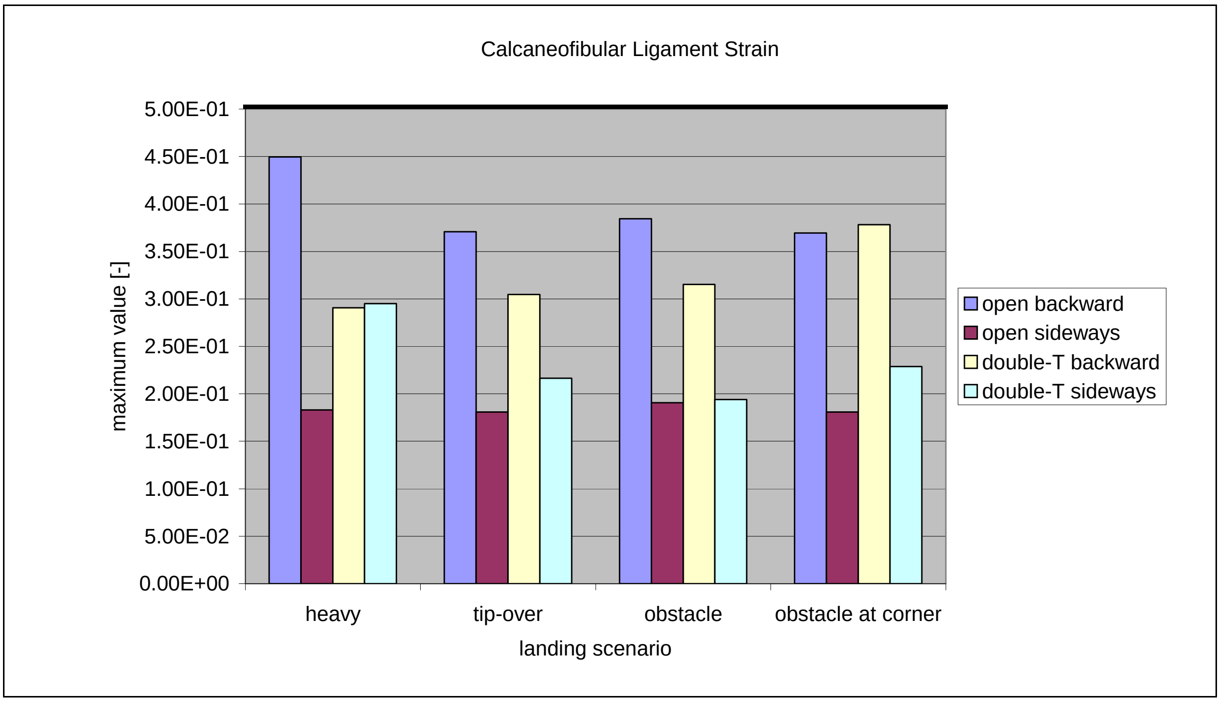

Figure 6 Maximum calcaneofibular ligament strain resulting from the simulations.

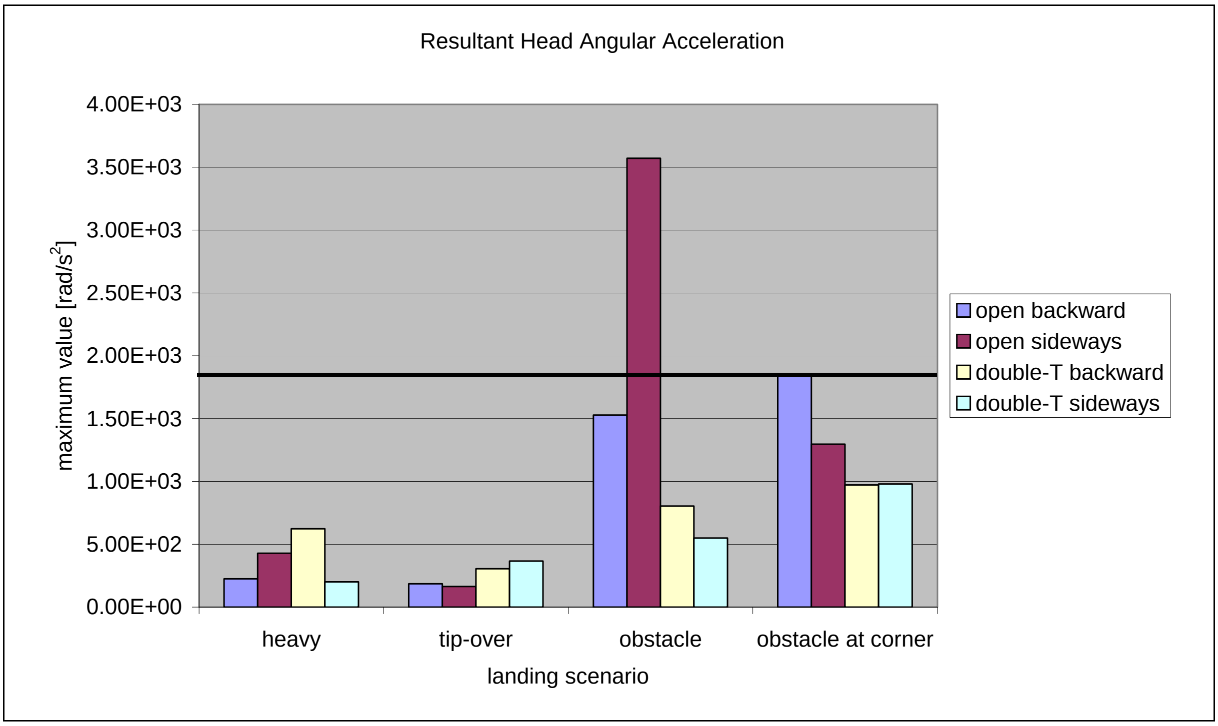

Figure 7 Maximum resultant head angular acceleration resulting from the simulations.

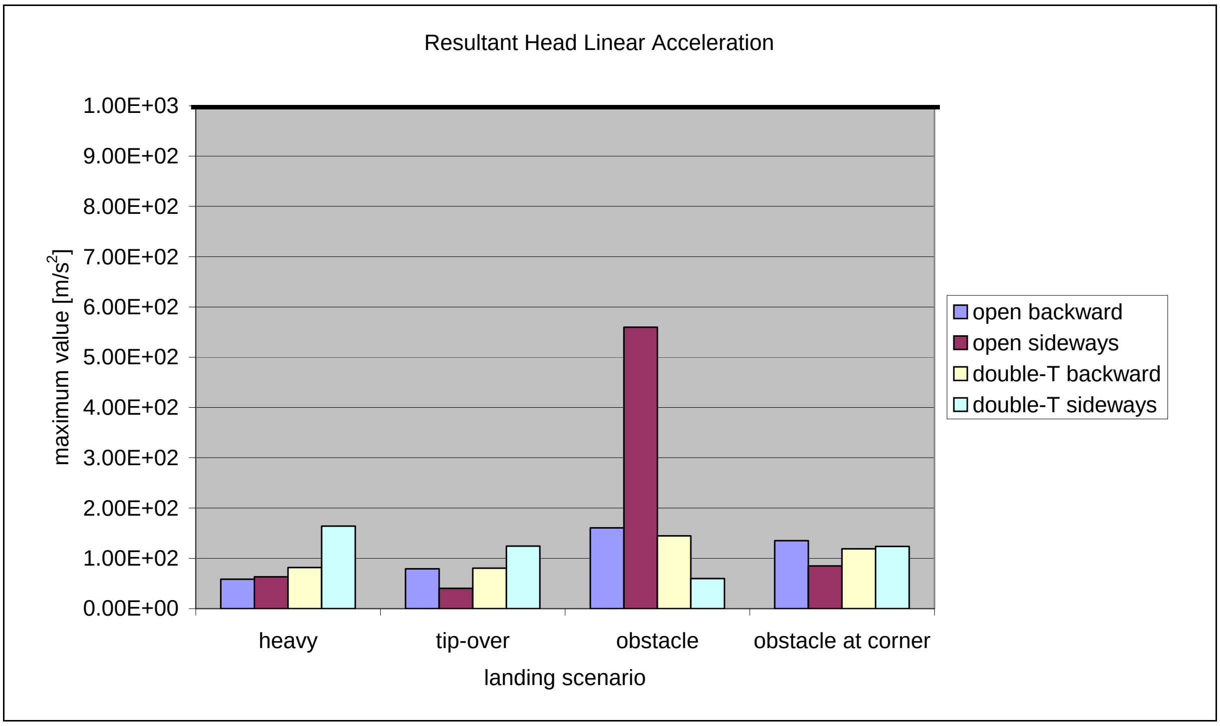

Figure 8 Maximum resultant head linear acceleration resulting from the simulations.

Appendix E Validation Results of the Flexible Basket Models

During the basket deformation tests displacement sensors were for each deformation configuration attached to different locations at the outside of the basket walls. The locations of the displacement sensors at the open and double T-partitioned basket are illustrated as yellow dots in Figure 1. Only the sensors that measured at least 20 mm displacement were used for validation of the flexible basket models. The names of those sensors are given in Figure 1. The points called ‘a’ were the sensor locations at the A deformation configuration, ‘b’ at the B deformation configuration etc. ‘x’ means frontal direction of the basket, and y means lateral direction. The arrows point in the displacement directions which are defined as positive. The maximum displacements measured at the location of the push block at the front side of the basket are given in Table 1. The results of the displacement sensors measuring less than 20 mm displacement were not used for validation of the flexible basket models, because the setting of the wicker walls was about 10 mm. The results of the basket models with the best fitted material parameters and the experimental results are shown in Figures 2 to 9.

Table 1 Maximum displacements at the location of the push block at the front side of the basket.

Deformation Configuration	Maximum displacement [mm] Open basket		Maximum displacement [mm] Double T basket	
	x	y	x	y
A	67	-	55	-
B	87	-	20	-
C	40	38	9	5
D			25	-

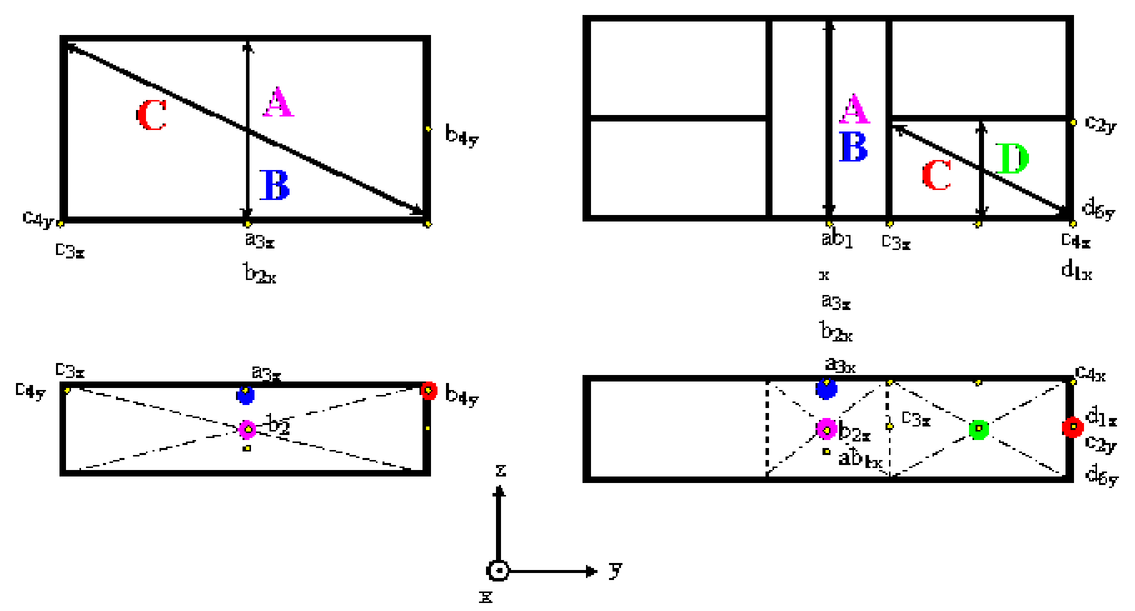

Figure 1 Locations of displacement sensors at the open and double T-partitioned basket that at least measured 20 mm displacement during the deformation experiments.

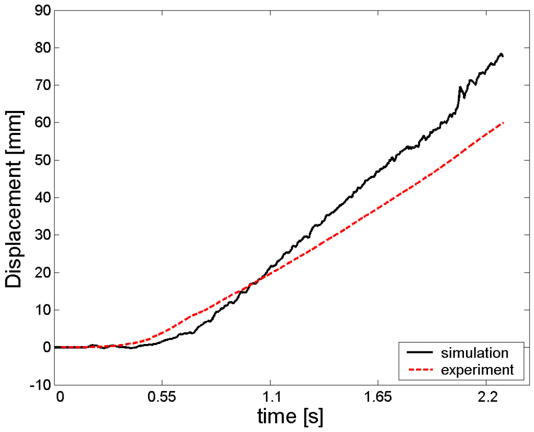

Figure 2 Measured and simulated displacement of the open basket at location 'a_3' in x-direction.

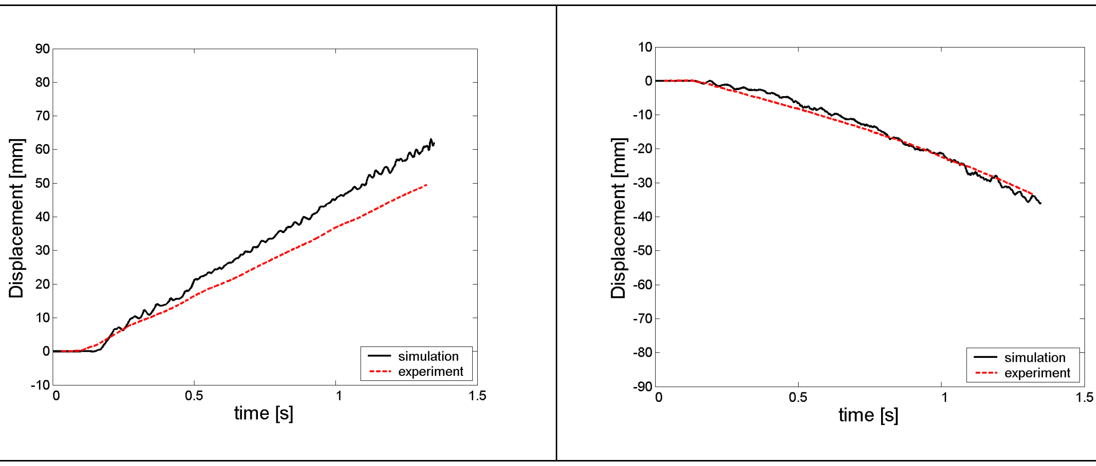

Figure 3 Measured and simulated displacement of the open basket at location 'b_2' in x-direction (left) and 'b_4' in y-direction (right).

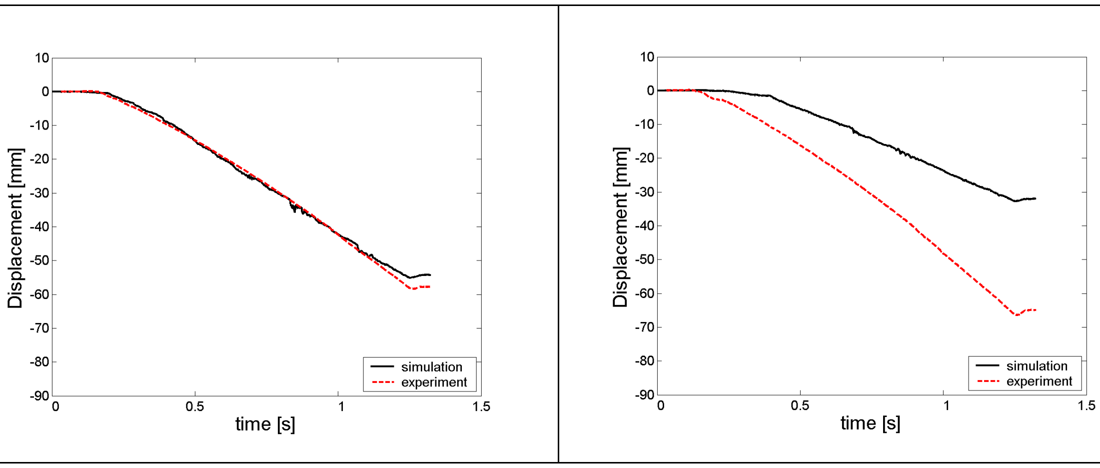

Figure 4 Measured and simulated displacement of the open basket at location 'c_3' in x-direction (left) and 'c_4' in y-direction (right).

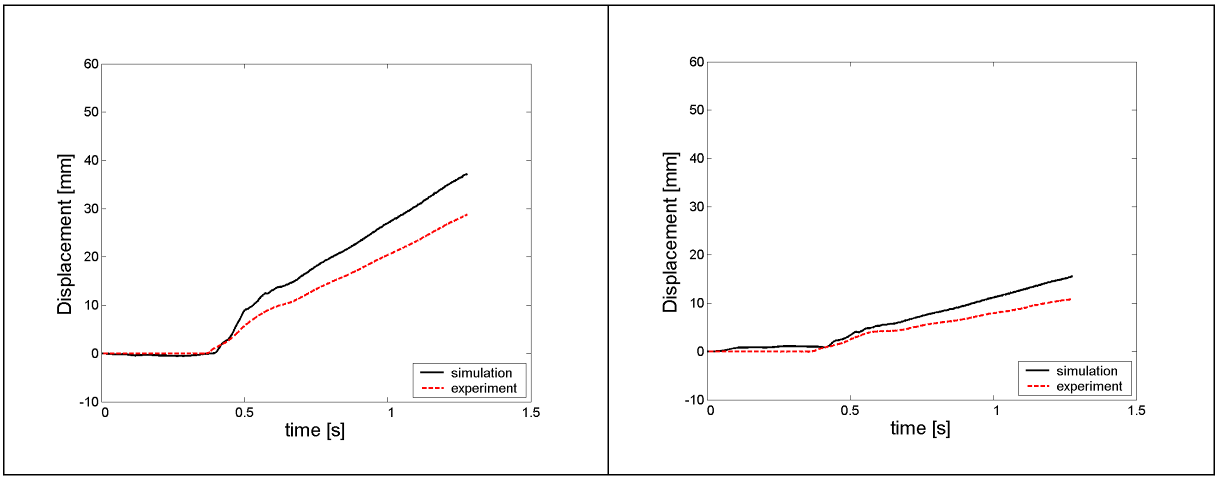

Figure 5 Measured and simulated displacement of the double T-partitioned basket at location ‘a_1’ (left) and ‘a_3’ in x-direction (right).

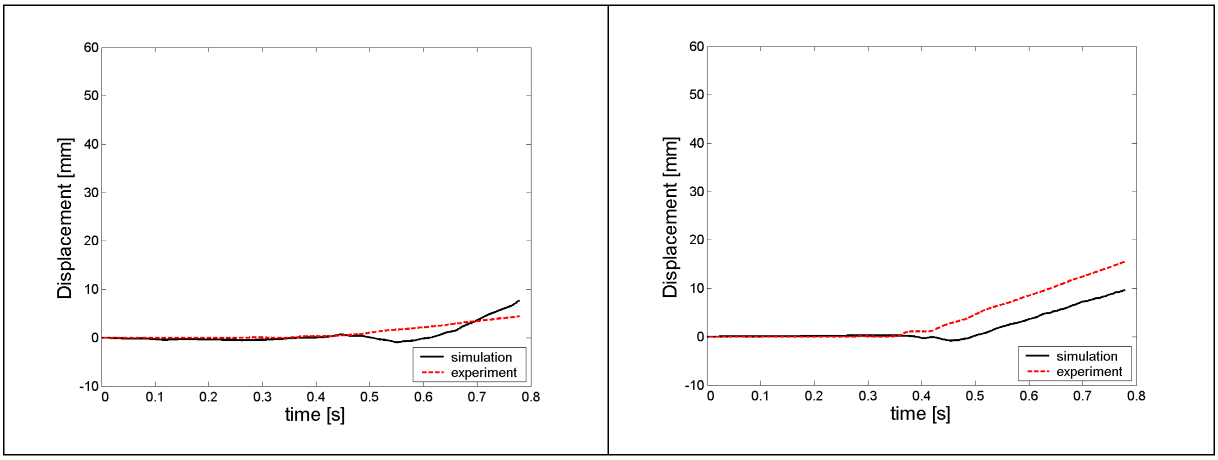

Figure 6 Measured and simulated displacement of the double T-partitioned basket at location ‘b_1’ (left) and ‘b_2’ in x-direction (right).

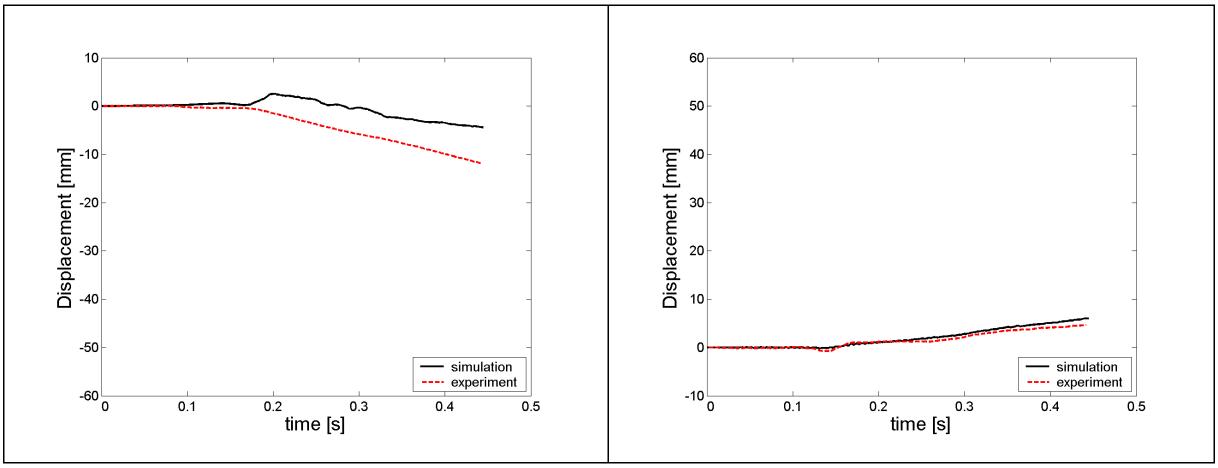

Figure 7 Measured and simulated displacement of the double T-partitioned basket at location ‘c_3’ (left) and ‘c_4’ in x-direction (right).

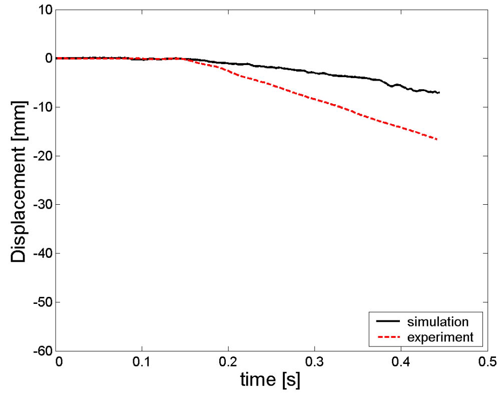

Figure 8 Measured and simulated displacement of the double T-partitioned basket at location ‘c_2’ in y-direction.

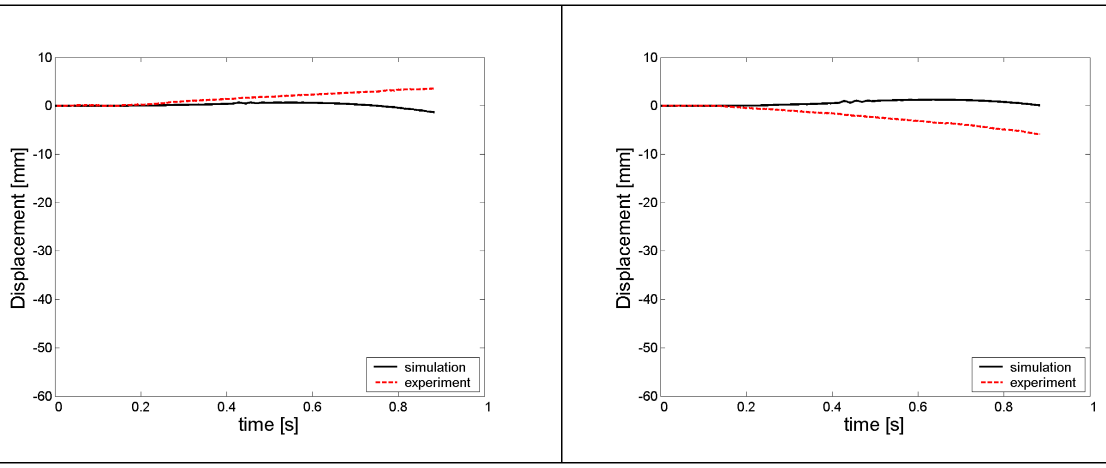

Figure 9 Measured and simulated displacement of the double T-partitioned basket at location ‘d_1’ in x-direction (left) and ‘d_6’ in y-direction (right).