

Comparative head injury risk analysis for cyclists wearing helmets during collisions: Real-world case investigations

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Abstract Cycle helmets have continued to increase in popularity since their introduction half a century ago. Many studies indicate that overall, head injury can be significantly reduced by wearing them. This study was conducted using two distinct sets of real-world cycling collision data from Ireland, namely cases involving police collision reports and cases involving admission to a hospital emergency department. The analyses sought to simulate and analyse the protective performance of cycle helmets in such collision scenarios, by comparing the Head Injury Criterion score and peak head accelerations, both linear and angular. Cycle collisions were simulated using the specialised commercial software MADYMO. From the simulation results, these key metrics were compared between the same-scenario helmeted and unhelmeted cyclist models. Results showed that the inclusion of bicycle helmets reduced linear accelerations very significantly, but also increased angular accelerations significantly compared to unhelmeted situations. Given the modest protective performance of cycle helmets against angular accelerations, it is recommended that cycle helmet manufacturers and international test standards need to pay more attention to head angular accelerations.

NOTATION

a acceleration
v velocity
t time
HIC Head Injury Criterion

INTRODUCTION

Currently, the Irish Road Safety Authority is funding a project being undertaken at University College Dublin to study the protective performance of cycle helmets. The main objective of this project is to pave the way for recommended policies which will reduce cyclist fatalities and injuries. In order to study the kinematics involved in cyclist collisions as well as the specific injuries mechanisms and points of contact on the vehicles, a number of real collisions for which data from police reports and coroner reports was available have been reconstructed using mathematical dynamic model (MADYMO) simulation software. One of these fatality cases involved a male cyclist from a rural setting, for which the methodology as well as the results are presented in this paper.

Summary of cyclist epidemiology

Pedal cycling is a vulnerable mode of transport. The rider position, the instability of travelling on a two-wheel vehicle, the height of the cyclist above the ground, the fact that cyclists lack the protection of a protective frame like motorists, all contribute to the incidence and severity of injuries in cycling. There is also a high risk of a cyclist being run over by another vehicle after a fall.

According to a British study [1], the most common cycle injuries were to upper limbs, accounting for 38% of all of the casualties presenting to hospital, followed by injuries to lower limbs (20%). Injuries to the head and neck accounted for some 11% of all casualties and injuries to the face accounted for 15% (See Figure 1).

Regarding trauma, the most common trauma to be sustained was an abrasion (41%) followed by laceration (35%). Simple fractures were common amongst those who had injured their upper limbs (36%) [1] (See Table 1).

According to data from the European APROSYS project [2], most of the cyclists were struck by a passenger car (86–89%). Therefore, the collision reconstruction presented in this paper of a 27-year-old cyclist struck by a passenger car travelling at 15 m/s (54 km/h) in a rural area can be said to be reasonably representative of the European as well as Irish epidemiology.

Review of previous literatures

Several previous studies have involved the reconstruction of pedestrian real-world collisions, using multi-body models, but not cyclists [2-6]. For example, Coley et al. [3] reconstructed a real-world fatal pedestrian collision involving a ‘family-size car’ and a small female using TNO’s female pedestrian model (1.53-m tall) and an ellipsoid-based vehicle modelled by ellipsoids. Yao et al. [6] reconstructed a non-fatal collision involving a 7-year-old pedestrian versus an Opel, using different numerical methods: multi-body system (MBS) vehicle model and Chalmers MBS pedestrian model [5]; facet vehicle model and facet pedestrian model; and finite-element method (FEM) vehicle model and facet pedestrian model. Authors concluded that the collision outcomes were significantly affected by initial posture and orientation of the pedestrian. On comparing the various numerical methods, the kinematics were found to be quite similar, but there were variations for the head injury results [6].

Of the cohorts of vulnerable road users, cyclists have been the subject of less research in recent years than compared with pedestrians. However, cyclist safety is beginning to get more attention from the scientific community. One of the first studies where MADYMO was used to model vehicle–cyclist impacts found that the kinematics of cyclists were similar to those of pedestrians but with the head impact location being more rearwards for cyclists, as the centre of gravity of cyclists is usually higher than pedestrians [4]. Maki et al. [7] carried out a study to compare the injuries sustained by cyclists and pedestrians when struck by vehicles and the associated injury mechanism through the analysis of collision data and mathematical simulation using MADYMO, with the vehicle contact characteristics used proposed by Ishikawa et al. [8].

REAL-WORLD COLLISION DATA

Thanks to the cooperation of the Irish National Police, the data required for the reconstructions have been provided by the police station and included a detailed account of the collision, as well as witness statements and a hospital report. The following is the summary of the collision: A 27-year-old male (not wearing a helmet) was riding a bicycle home along a rural road from the passenger’s off side (i.e. driver’s left). The vehicle, a passenger car, approached from the cyclist’s back, travelling at a speed of approximately 54 km/h (15.0 m/s) according to skid mark estimations by police. The driver, may be due to effect of alcohol, struck the rear side of the bicycle before braking. The centre of the bicycle was on the left of the vehicle centreline. The cyclist was separated from the bicycle, wrapped around the bonnet and travelled up the near side of the bonnet, striking his head on the near-side edge of the windscreen near the left A-pillar before coming away from the vehicle. The cyclist then landed on the road side (see Figure 2). The bicycle was thrown into the air and ended up behind the car’s final resting position.

Post impact inspection of the car vehicle provided more information regarding the initial impact between the cyclist and the car’s front (see Figure 2 and 3). The windscreen was broken with a common radial impact fracture pattern near the bottom near-side corner of the windscreen. Also, the near-side headlamp was broken.

Injuries

The injuries sustained by the deceased were closed head injury, fractured right ribs #2-#11 with haemothorax and contusion of right lung, and the cause of death recorded in the post-mortem report was ‘due to a closed head injury with a hinge fracture at the base of the skull and sub-arachnoid haemorrhage’. The injuries are given in detail in Table 2.

(1) Head: lateral to left eye 1cm; hinge fracture skull extending through both petrous bones, extending posteriorly along the line of the occipital parietal fissure on the left side and on the right near same. There was a 1cm overlap posteriorly and an extension on the right side superiorly 1cm. Diffuse sub-arachnoid haemorrhage most marked on the basal region 1mm maximum thickness.

(2) Thorax: fractured right ribs #2-#11 posterior medial scapular line with extensive haemorrhage beneath the parietal pleura which was punctured over fractured #2-#5 ribs.

(3) Upper limbs - abrasions on the back of right forearm multiple.

(4) Lower limbs - right knee two 5mm each abrasions.

MODELLING METHODOLOGY

Numerical simulation of vulnerable road users collisions is becoming popular in the field of impact biomechanics, and modelling of human bodies is becoming more and more biofidelic utilising both of multi-body and Finite Element (FE) approaches, including the scalable model for MADYMO version 7.3 used in this project. The geometry of this model is represented by ellipsoids, which result in reasonably short computation time.

Bicycle model

Bicycle dimensions have been adapted from [9], as have bicycle contacts, weight and moments of inertia [9]. Then, an outline of the main components was made from the police photo and then rescaled, then recreated in MADYMO (Figure 4). The model was constructed so that each of the joints has appropriate freedom of motion – for example the wheels rotate freely as do the pedals and the steering. In the reconstruction, a single, high stiffness characteristic adapted for all the bicycle components has been used. Bracket joints were used to join the rigid components.

Cyclist model

In this case, the cyclist's gender, age, height and weight were known, so the model was scaled accordingly.

Vehicle model

The vehicle involved was a Ford Escort. A multibody vehicle model was built with MADYMO, based on the simplified dimensions of that very model. The contact characteristics of all contacts were adopted from [10] and [11] (See Figure 6). Only the contact characteristic of the cycle helmet was acquired from a drop test conducted in UCD according to the European standard for cycle helmet (EN 1078 and EN 1080). Figure 6 shows diagrams for the headform on bonnet and legform on bumper test results.

Helmet model

A cycle helmet model was constructed in ABAQUS and exported to MADYMO utilizing the CAD model provided by its manufacturer. The commercial brand of this cycle helmet is Lazer Armor (Figure 7).

The Lazer Armor model was then imported into MADYMO and positioned in a manner akin to the manufacturer's fitting instructions. The chinstrap was modelled as restraint points, as a simple test conducted at UCD showed that when the exerted force was increased to be of a certain extent, the bolts would be broken before any significant extension of the chinstrap. The inertial properties of the cycle helmet were calculated in a similar way to the motorcycle helmet in MADYMO library, that is, to consider the cycle helmet as a hollow sphere.

Initial conditions

The involvement of many vehicles in the collision make the task of modelling the kinematics in a simulation complicated. The following initial conditions were analysed and tuned before finding a set of parameters that resulted in a reasonable reconstruction: initial car speed and car deceleration, bicycle crank rotation, hip, knee and ankle rotations of both cyclist's legs, steering direction, head rotation, trunk bending and twisting. A total of 11 different parameters are presented in Table 2.

RESULTS AND DISCUSSION

According to [11], vulnerable road users-related collisions are difficult to simulate due to the high number of unknown initial conditions, some of which have a wide range of possible values, and many of which interact. In this particular collision case, the post-impact kinematics involved the cyclist separating from the bicycle, wrapped around the bonnet and traveled up the side of the bonnet. The head and/or shoulder then stroke the windscreen (likely near the left A-pillar) before coming away from the vehicle. The cyclist then flew over the vehicle before landing on the ground. The bicycle was thrown into the air and then ended up behind the vehicle. A total of 55 simulations were carried out, varying 11 of the initial conditions (Table 2).

Regarding the modelling methodology, in order to reconstruct these collisions, multi-body models can be seen as sufficiently detailed. Reconstruction will be validated by the pre- and post-accident geometry of the accident scene, the points of impact on the motorized vehicle and the injuries of the cyclist involved, then finally by comparing injury criteria with known injury details.

Primary impact

The car impacted with the cyclist's left leg ($t = 0$ ms), corresponding with the right knee two 5mm each abrasions recorded in the post-mortem (Figures 8 and 10). The vehicle after collision had a broken headlamp, and Figure 9 shows the bicycle rear frame hitting the left headlamp. In the reconstruction, the cyclist's shoulder impacted the left corner of the windscreen (Figure 11), in agreement with the police data.

Secondary impact

The police data reported that after primary impact with the vehicle, the cyclist flew over the vehicle before landing on the ground and that the bicycle was launched into the air, flying in the opposite direction as the vehicle movement and finally lying on the ground behind the car (Figure 12).

Effect of wearing a helmet

As seen in Figures 13-15, the wearing of a cycle helmet in this particular real-world case decreased peak head linear acceleration for almost 55%, but only about 15% for head angular acceleration.

A HIC score of almost 25000 was recorded in the simulation at the moment of head impact with the ground. Since a HIC score of such value corresponds to a fatal collision, this correlates with the actual fatality sustained. The maximum angular acceleration also occurred at the moment of secondary head impact. There are many studies linking head angular acceleration with brain injuries, especially diffuse axonal injury, as this is caused primarily by head angular acceleration [12].

CONCLUSIONS

A real-world collision involving a male adult cyclist struck by a passenger car resulting in the death of the cyclist was modelled using MADYMO software. The height, weight and gender of the cyclist, the

geometry of the bicycle and the car were used to create the MADYMO models. Known initial conditions were set according to police reports, including vehicle markings, skid mark and witness statements. Other initial conditions were found by tuning the simulation and comparing the results with data from the police report. The criteria for verification is the pre- and post-accident geometry of the accident scene, the points of impact on the motorized vehicle and the injuries of the cyclist involved. Good correlations for most of the injuries are shown, means that simulation can provide more information about the causes of specific injuries.

This study has shown that it is possible to reconstruct a collision if sufficient data is provided with reliable result. This information can be used to understand the kinematics of cyclist collisions with various modelling parameters. For cycle helmets, they generally lower the magnitude of linear accelerations on the head. However, cycle helmets may not be able to reduce head angular accelerations significantly.

FIGURES AND TABLES

Figures

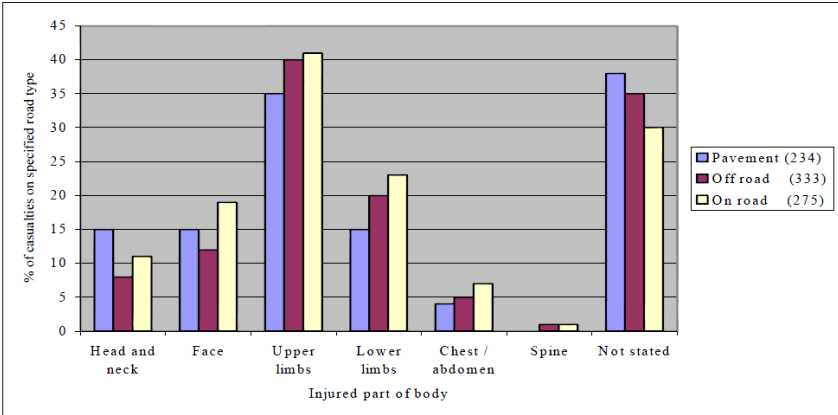


Figure 1. Body part injured by location of collision (adapted from [1]).

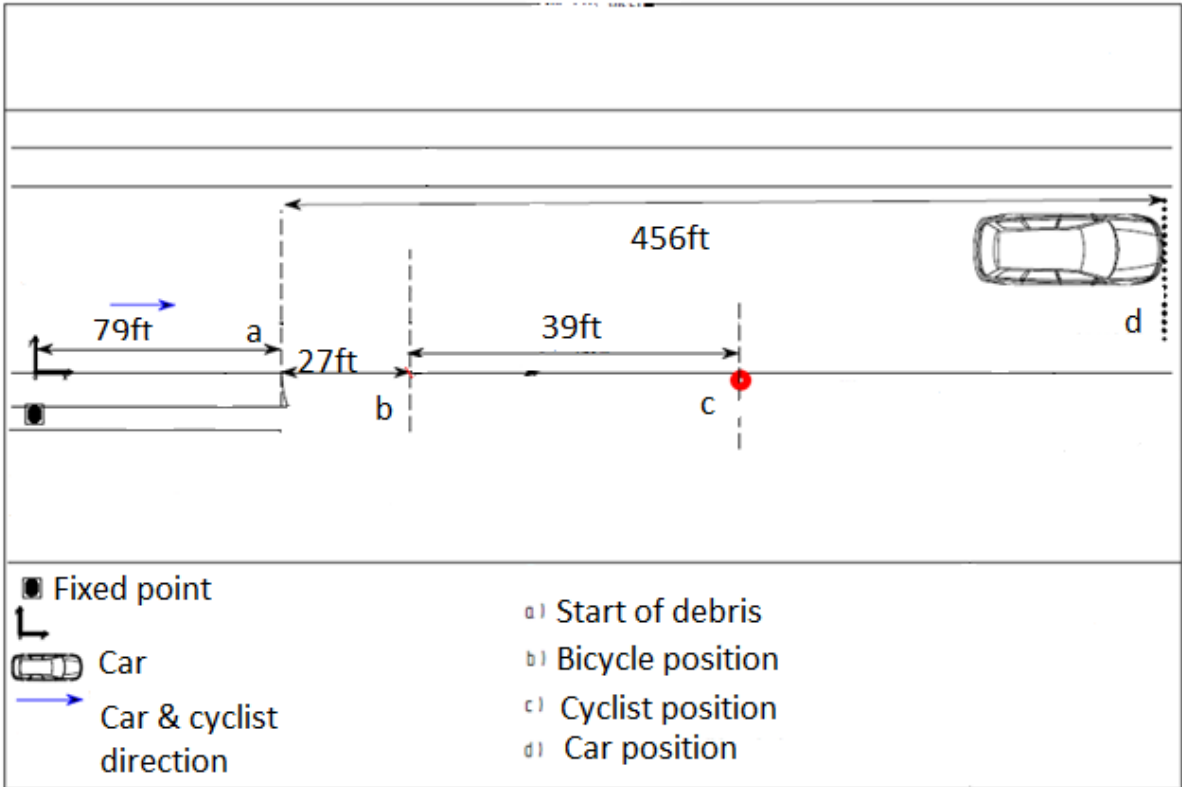


Figure 2. Rough sketch of scene.

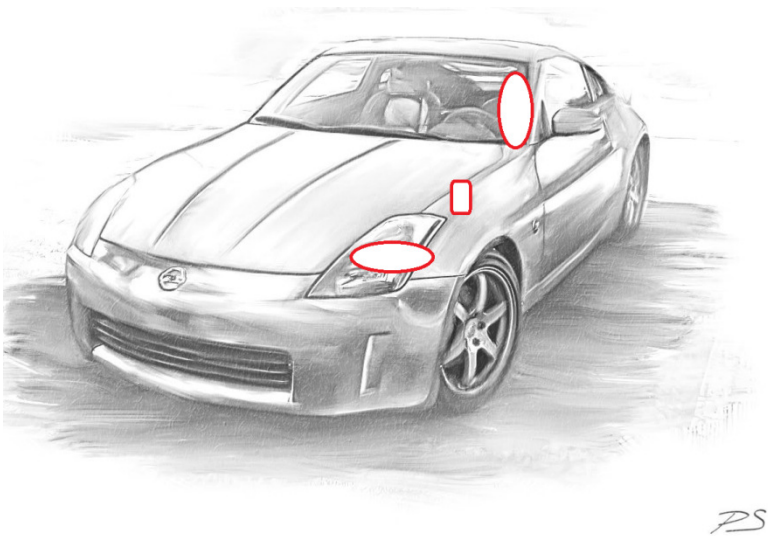


Figure 3. Vehicle contact diagram.

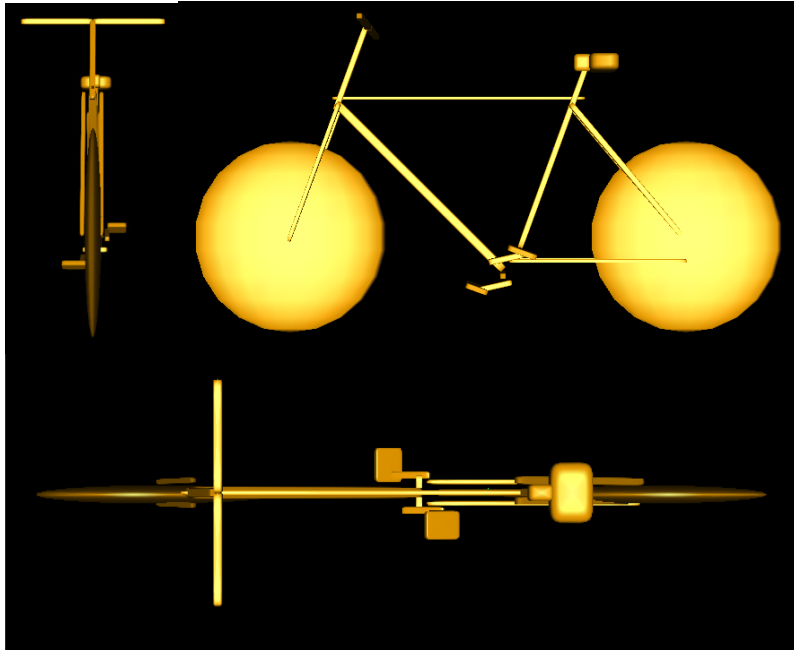


Figure 4. MADYMO model of the bicycle.

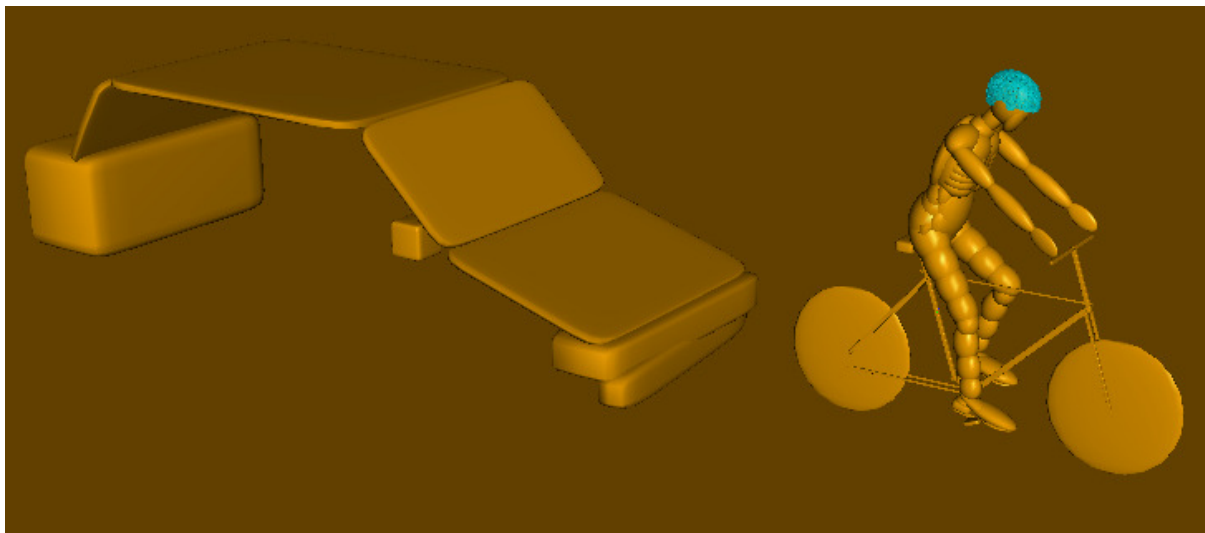
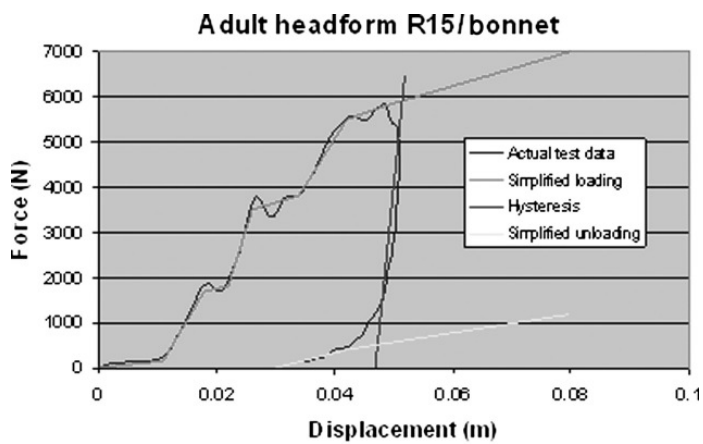


Figure 5. Collision assembly.



(a)

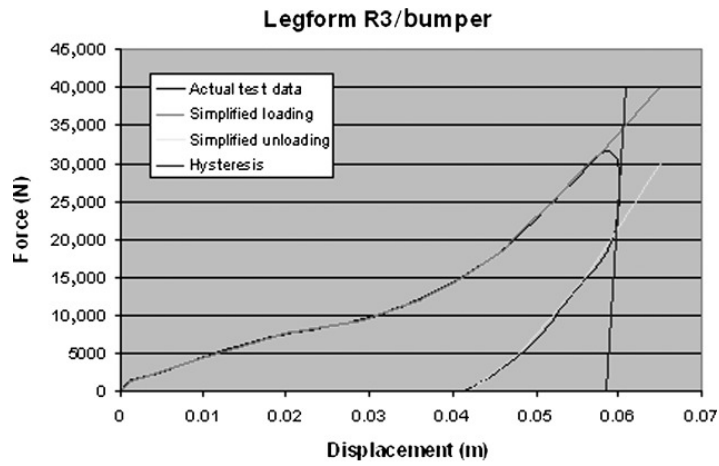


Figure 6. Diagrams of loading, unloading and hysteresis functions used in vehicle modelling (adapted from [11]).

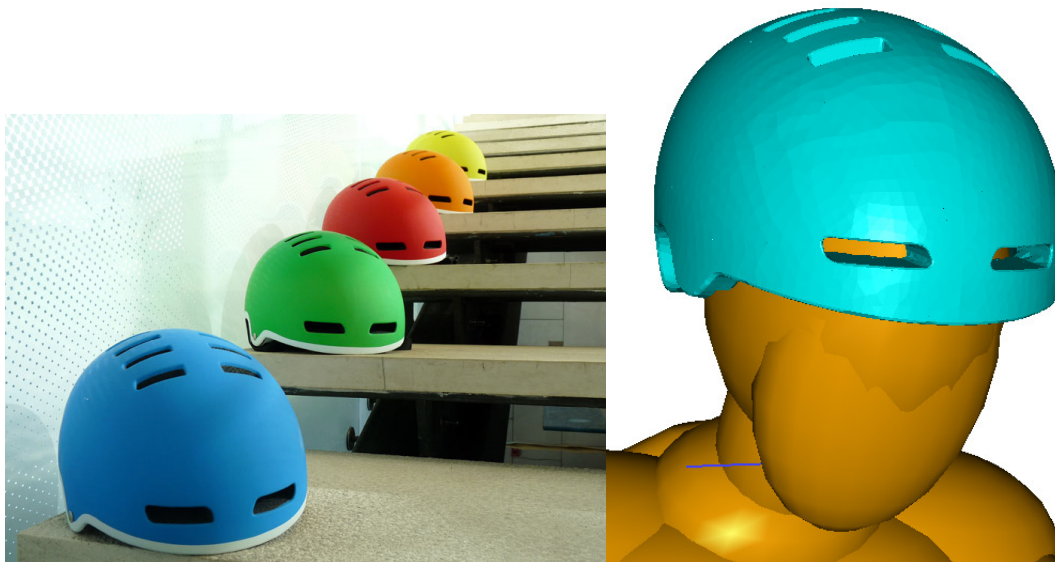


Figure 7. Lazer Armor helmet (left: on sale, right: its finite element model in MADYMO).

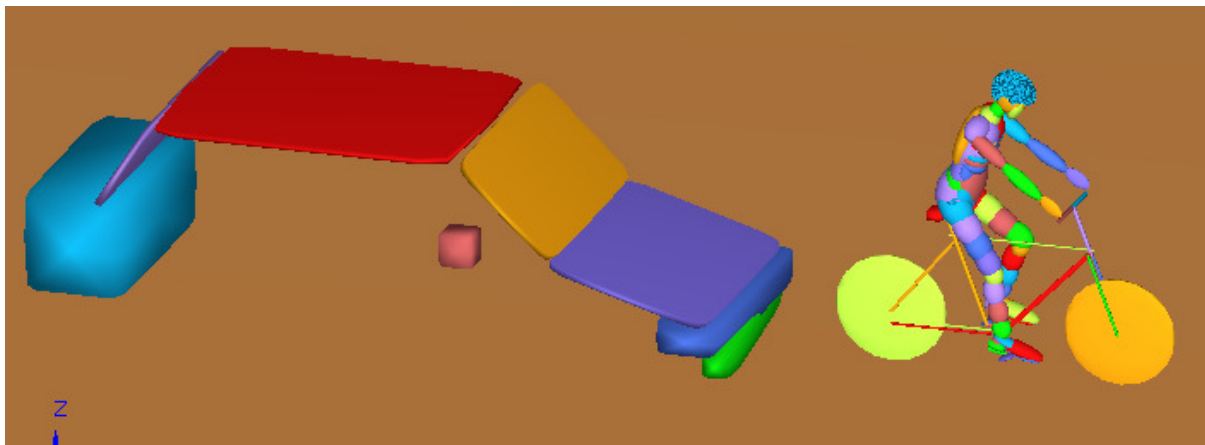


Figure 8. Simulation screenshots at 0ms.

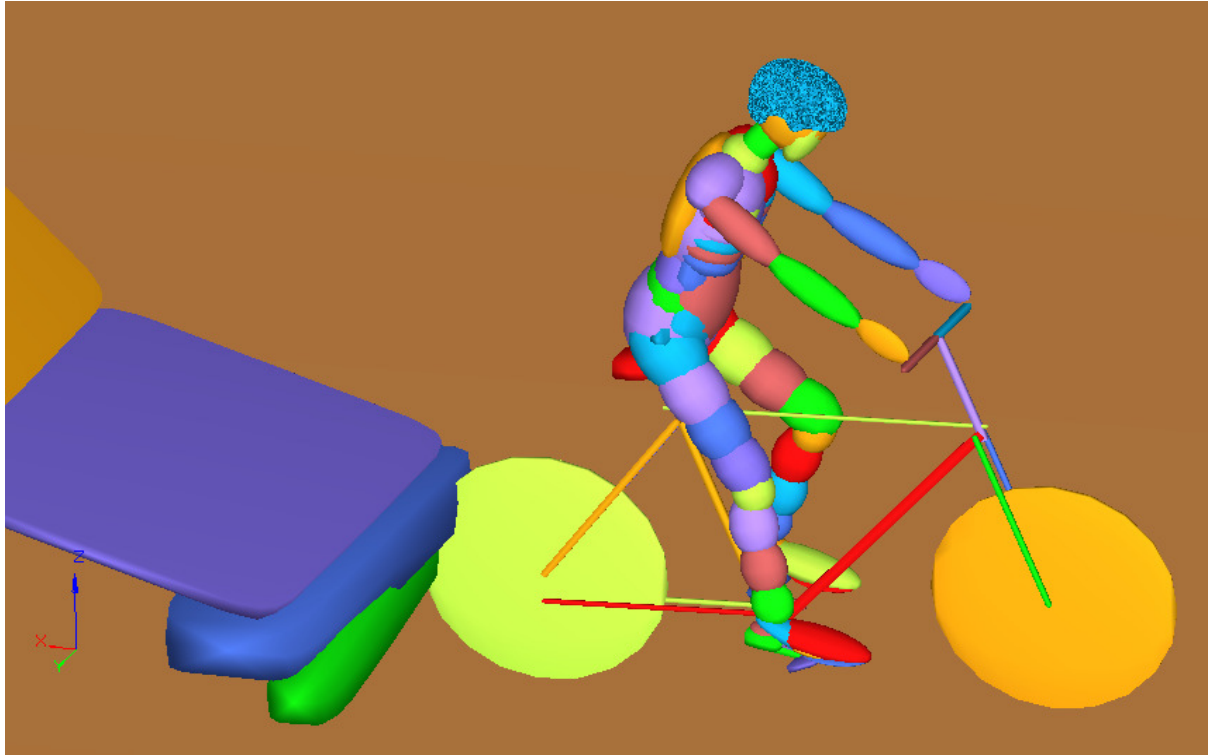


Figure 9. Simulation screenshots at 34ms.

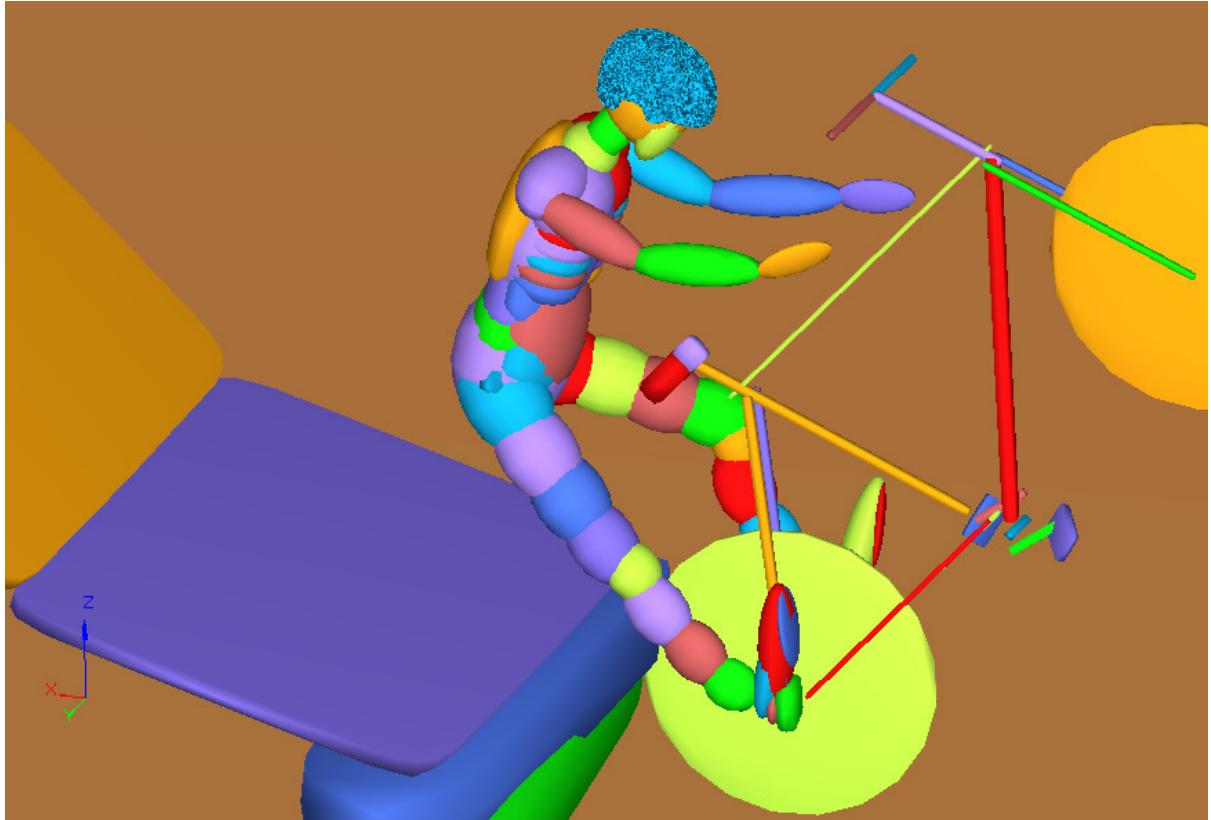


Figure 10. Simulation screenshots at 93ms.

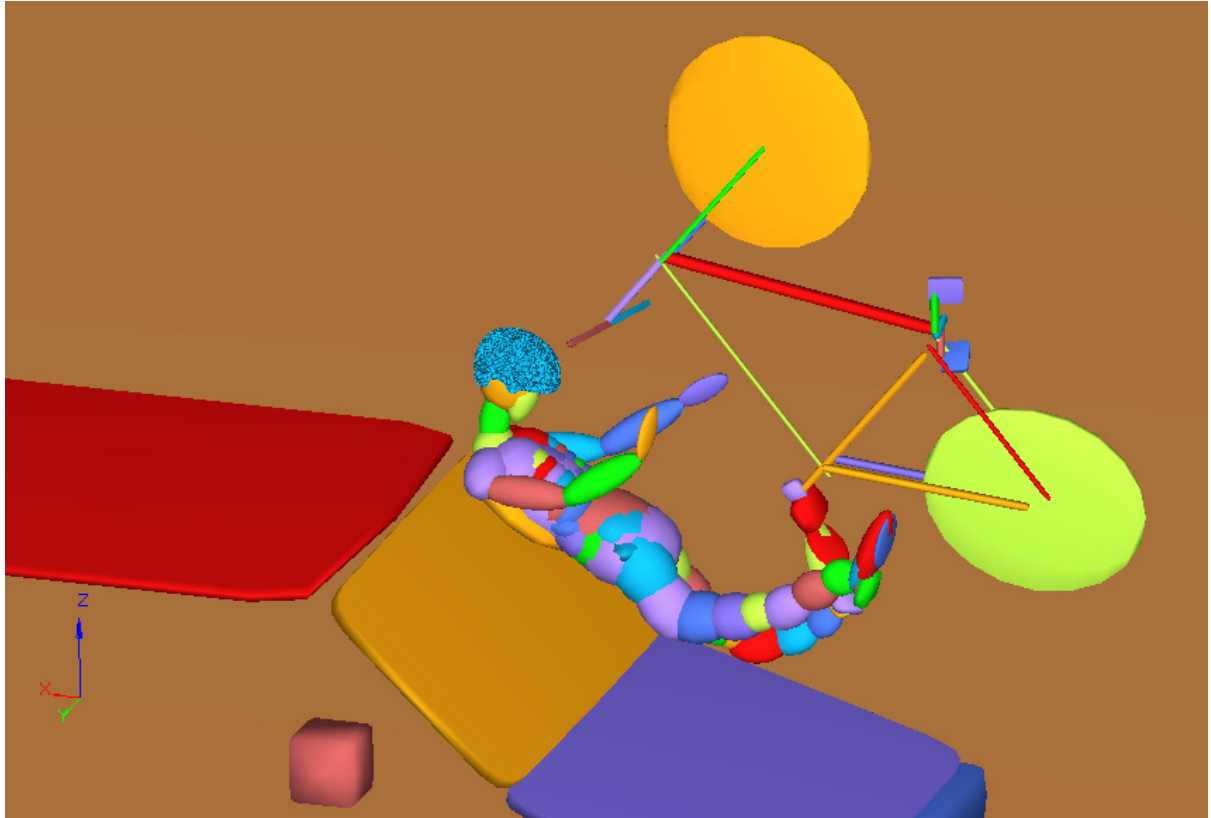


Figure 11. Simulation screenshots at 175ms.

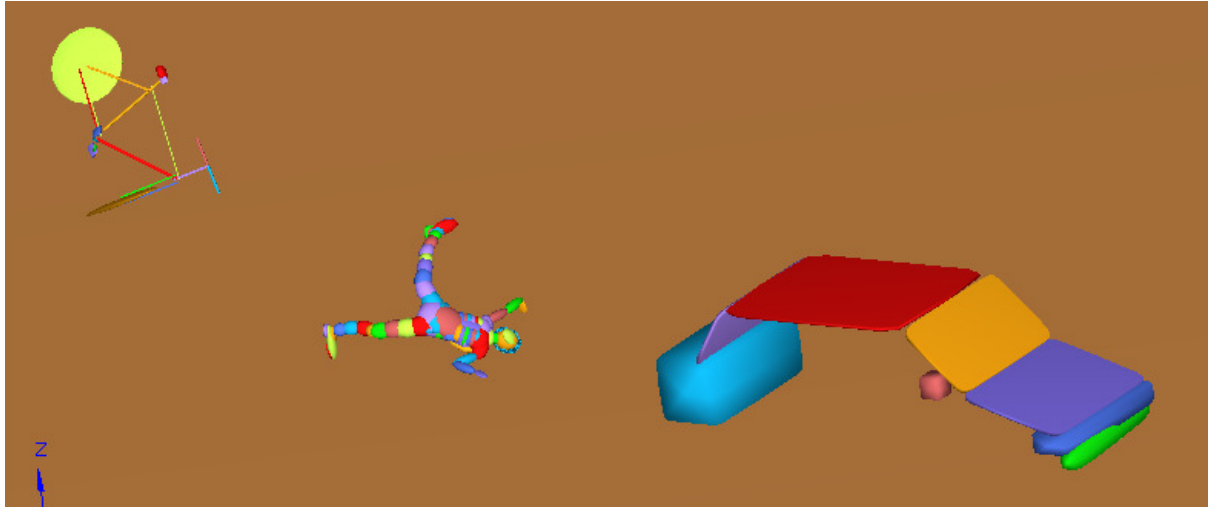


Figure 12. Simulation screenshots at 1441ms.

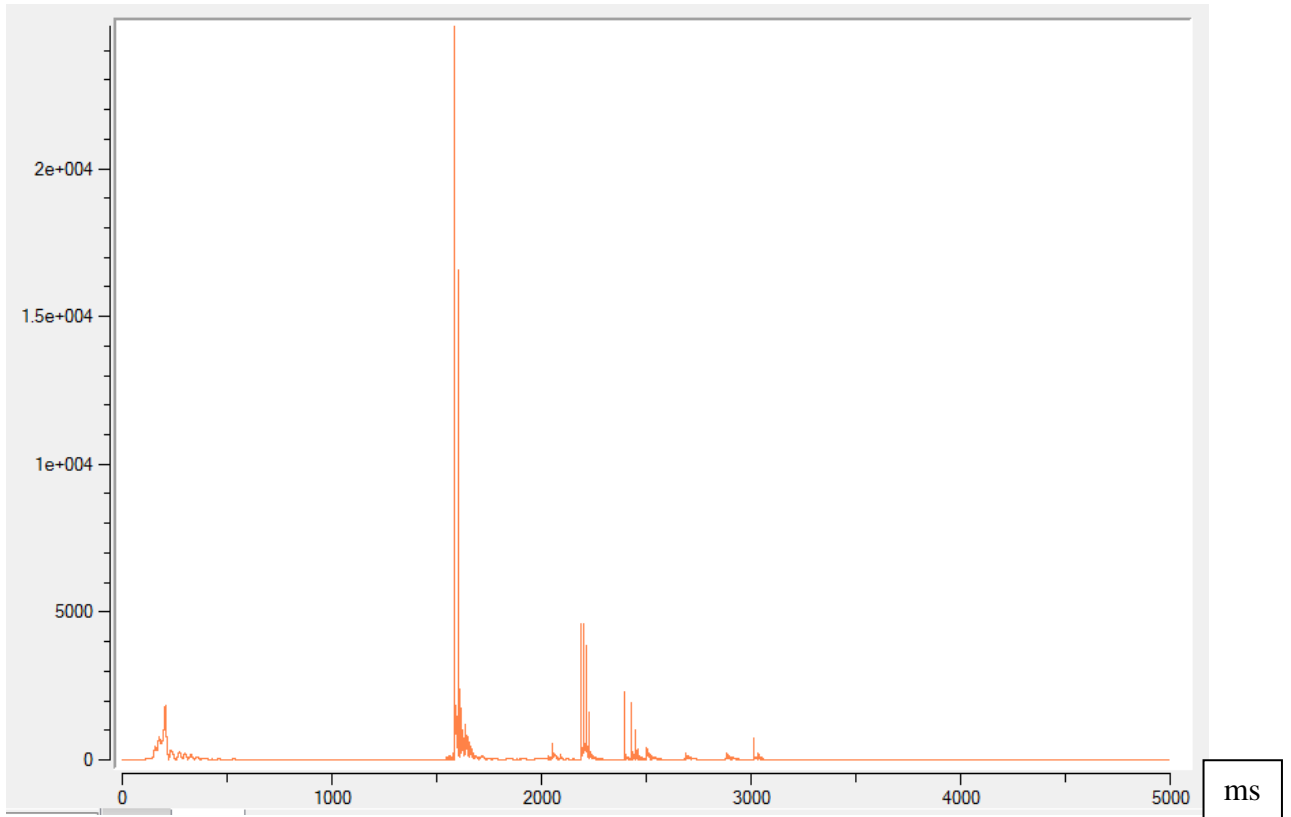


Figure 13. Unhelmeted HIC score during the collision.

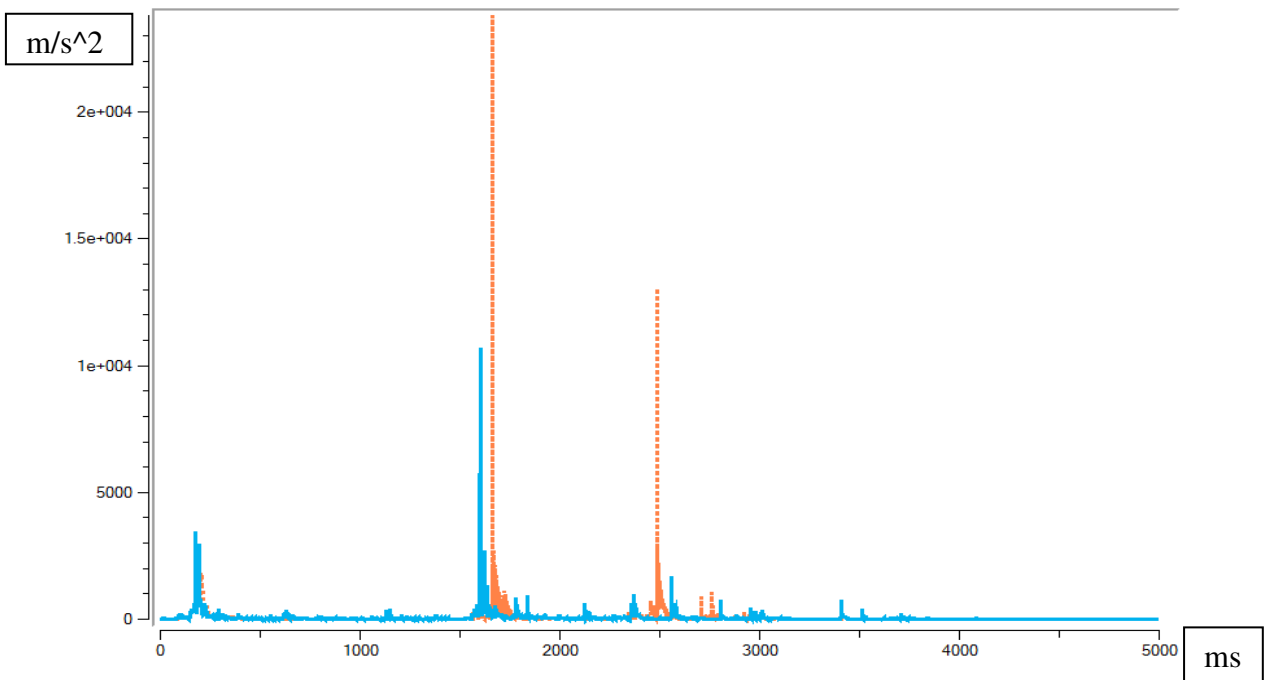


Figure 14. Unhelmeted (dashed) and helmeted (continuous) linear acceleration during the collision.

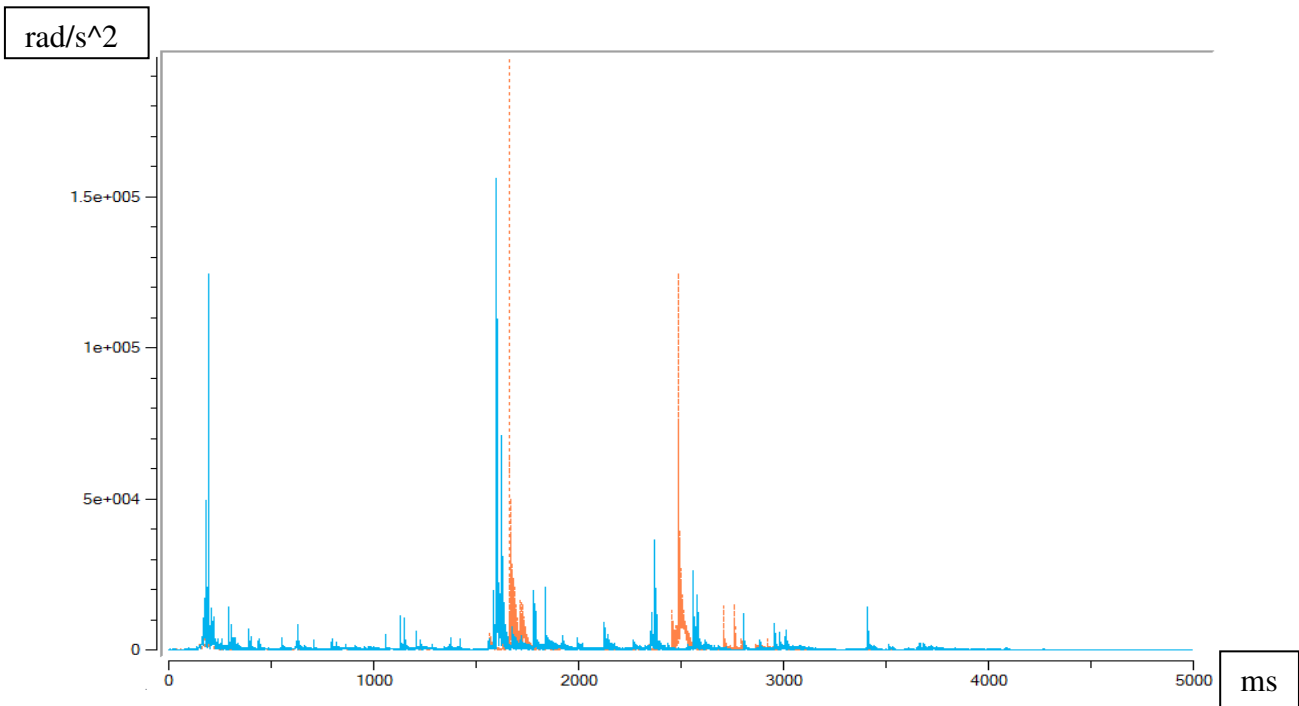


Figure 15. Unhelmeted (dashed) and helmeted (continuous) angular acceleration during the collision.

Tables

<i>Type of trauma</i>	<i>Head & neck</i>	<i>Face</i>	<i>Upper Limbs</i>	<i>Lower limbs</i>	<i>Chest / abdomen</i>	<i>Spine</i>
	%	%	%	%	%	%
Abrasion	41	64	40	49	40	17
Contusion	26	21	10	17	31	33
Laceration	35	40	7	22	9	-
Sprain	7	-	25	18	7	50
Simple fracture	3	4	36	8	11	-
Complex fracture	-	2	4	2	-	*
Query internal organ damage	2	1	-	-	16	-
Not stated	1	-	-	-	-	-
Base	86	117	310	159	45	6

Table 1. Type of trauma [1].

Initial condition	Range of values	Final
Pre-impact speed (m/s)	13.0; 13.5; 14; 14.5; 15.0; 15.5; 16	15.0
Vehicle deceleration (m/s ²)	7.2 - 7.5	7.35
Cycle steering (rad)	-0.2; 0; 0.2	0
Cycle offset (m)	To the left of the car: 0.0 - 0.9	0.5
Pedal at top	Left; right	Left
Initial car - cycle gap (m)	0.1 - 0.8	0.6
Head rotation (rad)	-0.2 -> 0.2	0
Left hip rotation (rad)	0 - 2	0.84

Right hip rotation (rad)	0 - 2	0.75
Left knee rotation (rad)	0 - 2	1.35
Right knee rotation (rad)	0 - 2	0.38

Table 2. Initial conditions.

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