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Numerical analysis of a pedestrian to car collision — Effect of variations in walk

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Abstract

This work is focused on the modelling of car to pedestrian crash scenario. Virtual hybrid human body model VIRTHUMAN as well as a simplified model of car chassis is modelled under Virtual Performance Solution software. The main idea of the work is the investigation and sensitivity analysis of various initial conditions of the pedestrian during frontal car crash scenario, such as position of the extremities due to different step phases or turning of the pedestrian around his own axis. The experimental data of human gait measurement are used so that one human step is divided into 9 phases to capture the effect of walk when the pedestrian crosses a road. Consequently, the influence of different initial conditions on the kinematics, dynamics of the collision together with injury prediction of pedestrian is discussed. Moreover, the effect of walk is taken into account within translational velocities of the full human body and rotational velocities of the extremities. The trend of the injury prediction for varying initial conditions is monitored. The configurations with zero and non-zero initial velocities are compared with each other, in order to study the effect of walking speed of the pedestrian. Note that only the average walking speed is considered. On the basis of the achieved results, the importance or redundancy of modelling the walking motion and the consideration of different step phases in the car-pedestrian accident can be examined.

Keywords: human body model, car-to-pedestrian collision, gait modelling, pedestrian velocity, injury prediction

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1. Introduction

The purpose of this paper was the investigation of virtual performance in the modelling of the pedestrian to car crash scenario with respect to various initial conditions of the pedestrian in front of the car. The car was simplified to a model of a car chassis only, which is based on real geometry data. The fully validated model of a human body, VIRTHUMAN, was used for the simulations in Virtual Performance Solution software. Real experimental data of the human gait phases were investigated for the sensitivity analysis and the effect of various initial conditions (positions, translational and angular velocities) of the pedestrian on the injuries. Consequently, turning of the pedestrian around his own axis was considered, as well. As a result of the collision with the car, the probability of the pedestrian injury for the various body segments was evaluated on the basis of the EuroNCAP injury rating [4]. The aim of this paper was to assess the effect of the pedestrian motion on crash injury sustained by the pedestrian. Based on the results of gait simulations, one particular configuration was identified and applied in the simulations including initial velocities representing the gait of the pedestrian. The results of the injuries for the cases with zero (later referred to as the static case) and non-zero (referred to as the dynamic case) initial condition were compared with each other. Finally, for the purpose of considering

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a more realistic human locomotion, the initial angular velocities of extremities were defined for particular human joints and the results were compared with the translational velocity definition.

2. State of the art

2.1. Human body modelling

Currently, the virtual approach in the biomechanical field is of great interest to many researchers, especially as the virtual human models can be used in the analysis of various scenarios. Presently, the virtual prototyping in the automotive industry takes benefit from the numerical human models. The models are mostly based on the finite element method, a rigid body (articulated rigid bodies) or a hybrid approach that combines advantages of both approaches. The review of the current state of human biomechanical models is given in [27].

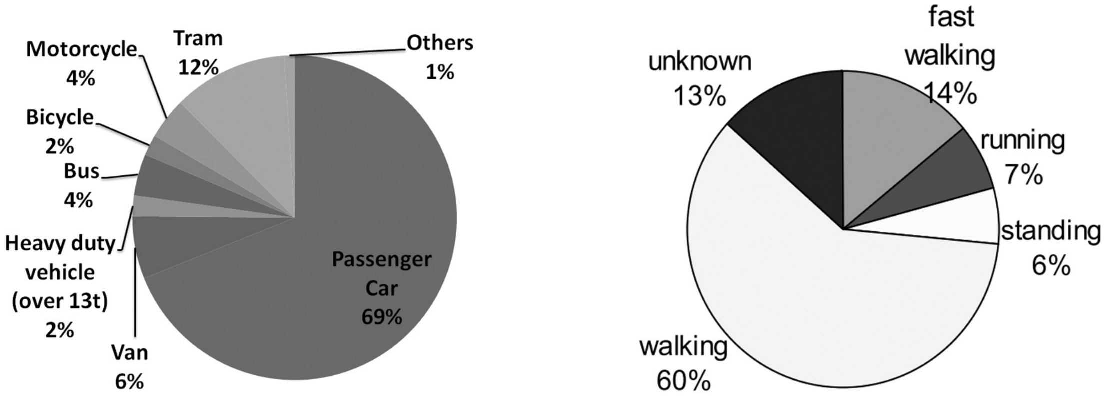
2.2. Injury scales

The pedestrian-to-vehicle collision is responsible for a significant number of deaths and serious injuries around the world (annually about 2 000 in the Czech Republic in 2014 [13, 14]; 7 000 in the UK, about 40 000 in the EU and about 1.2 million wolrdwide each year in 2010–2011 [13, 15] and [26]). The interest of research studies in the simulation of car crash accidents is motivated by the effort to further decrease the number of deaths and injuries from road traffic accidents [13], when accident occurs. Due to the advantage of numerical models, the car geometry (bonnet, windscreen etc.) can be easily optimized for a better protection of the pedestrian. For such analyses, appropriate human and car models are highly required as well as a detailed description of a real car-pedestrian accident for model validation. In order to conclusively describe the level of injury, to set up the relationship between the kinematics and dynamics values (force, displacement, velocity or acceleration) and the level of injury, several injury scale ratings were established. The Abbreviated Injury Scale (AIS) [17] is generally used for the medical description of injuries only. The EuroNCAP injury rating [4] and the Injury Severity Index (IrSix) [15] are used primarily in automotive industry for the specification of the injury criterion based on the mechanical quantities such as force, deformation, velocity or acceleration generated at particular body segments. In recent years a relationship between the medical (AIS) and engineering (EuroNCAP) injury ratings was specified as described in [3].

2.3. Car-to-pedestrian crash modelling

Pedestrians are the most vulnerable traffic users as they are exposed to high injury risk during a collision with vehicles. Recent European studies indicate that passenger cars are the ones most often involved in a collision with pedestrians. Fig. 1(a) summarises the various vehicle types involved in pedestrian collisions in the Czech Republic in the years 2009–2014, see [21].

With respect to the statistic results depicted in Fig. 1, the main interest is focused on passenger car to pedestrian collision. The collision of pedestrians with a vehicle can be divided into a primary contact (pedestrian to vehicle) and a ground contact. Significant injuries can occur in both situations – during the collision with the vehicle and also in the ground contact. Many studies [5, 6, 18–20] or [25] are focused on the primary contact. Although the statistics show that the majority of accidents occurs when the pedestrian is crossing the road (i.e., he is moving at the moment of collision), see Fig. 1(b), the effect of the pedestrian motion is not usually addressed during the collision investigation and pedestrian protection. Fig. 1(b) depicts the statistics of the pedestrian posture during car collision. Hamacher, Ramamurthy



(a) Distribution of vehicle types involved in pedestrian accidents in the Czech Republic in 2009–2014 [21]

(b) Posture of the pedestrian at the moment of collision [26]

Fig. 1. Statistical data of car-to-pedestrian crashes

and Yang in their works [5, 15, 26] discussed the position of both left and right legs of the pedestrian. Hamacher also tested the effect of the different pedestrian locations; moved in the range ±200 mm from the medium axis of the car. Simms in his work [19] considered different turning angles of the pedestrian (backward and frontward to the car). Recently, Li [12] in his work investigated the effect of gait stances on the upper limb injuries. The monitored value was the stress distribution on the tibia and femur bones for the struck and non-struck legs, respectively.

The modelling of a pedestrian traffic accident is a complex problem that requires proper description of the car model, human body model as well as detailed definitions of initial conditions of the accident scenario. Nonetheless, the effect of the different pre-impact conditions of the pedestrian (velocity, motion of the upper and lower extremities, turning angles towards the car etc.) is not usually taken into account in such researches. The present work analyses the human locomotion and the effect of step-phases on the probability of injuries in identical accident scenarios. Consequently, the effect of local angular velocities of the upper and lower extremities is discussed. The critical case of pedestrian's postures was analysed with the definition of non-zero initial translational and angular velocities and compared with static cases (zero initial velocities).

3. Method

The paper is focused firstly on the effect of the different pedestrian's postures during the crossing of the road (various step phases) and secondly on the effect of different turning angles of the pedestrian with respect to the car (towards the car or away from it). Thirdly, this study discusses the effect of pedestrian velocities (translational velocity of the pedestrian and rotational velocity of human joints) on the probability of injuries. The definition of the pedestrian velocity is based on the average velocity of normal walk, i.e. about 5 km/h [8, 21].

3.1. Human gait (locomotion) segmentation (phasing)

Human gait can be divided into several phases, such as right leg posed — left leg lifted up — legs are passing each other — left leg posed — right leg lifted up etc. Havelková in her

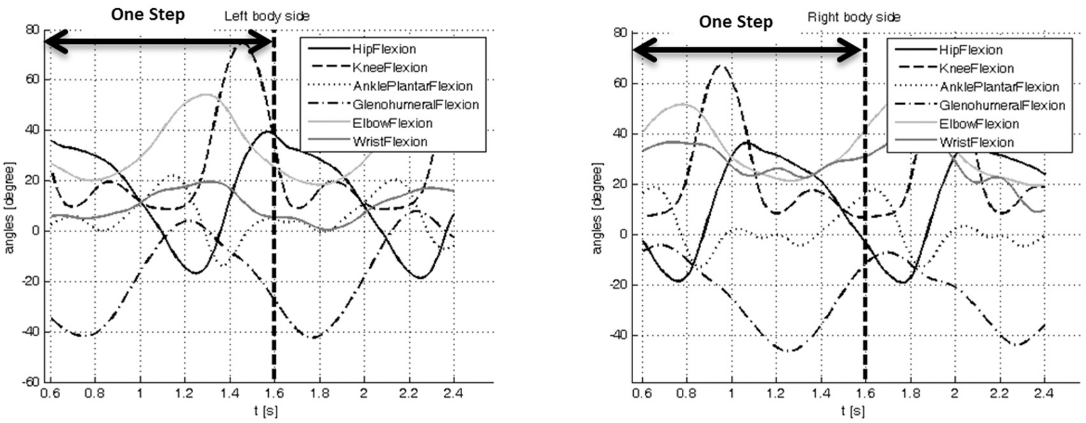


Fig. 2. Angles of rotation in human joints

work [7] published data of volunteer's locomotion measurement using Vicon motion capture system [22]. The trajectories of several well defined anthropometric points were analysed in AnyBody software [16]. This software allows us to simulate human gait and provides values of internal rotations and angular velocities of human joints that were used in the present paper. The monitored values were rotational angles and velocities (left and right extremities) of shoulders (glenohumeral), elbows, wrists, hips, knees and ankles (ankleplantar). The rotation angles of the left and right body segments during normal average walk are plotted in Fig. 2 and summarise in Table 1.

The curves in Fig. 2 cover the duration time of one step (double step) $t = 1.0$ s. The step of the human gait was divided into 9 phases, as indicated in Fig. 3. Note that the first and last configurations are identical. The particular configurations of the human gait are expressed in percentages, i.e., 0 % indicates the start of the step at $t = t_0 = 0.6$ s, and 100 % represents the same position at the end of this step, where $t = t_{\text{final}} = 1.6$ s. Hence the evaluated human step phases are assumed at 0 %, 12.5 %, 25 %, 37.5 %, 50 %, 62.5 %, 75 %, 87.5 % and 100 % of

Table 1. Human joints rotation angles in degrees for various step phases

Step Phases	**0%(1)**	**12.5%**	**25%**	**37.5%**	**50%**	**62.5%**	**75%**	**87.5%**	**100%**
Time [s]	**0.6**	**0.725**	**0.85**	**0.975**	**1.1**	**1.225**	**1.35**	**1.475**	**1.6**
L. Hip Flexion	36	32	27	15	−1	−16	−2	30	38
L. Knee Flexion	24	10	19	13	9	12	52	74	34
L. AnklePlant. Fl.	3	5	0	9	20	14	−13	−1	5
L. GlenoHum. Fl.	−35	−41	−37	−20	−4	4	−4	−13	−28
L. Elbow Flexion	27	21	21	27	40	52	52	36	25
L. Wrist Flexion	6	5	6	10	16	18	20	10	5
R. Hip Flexion	−3	−17	−7	27	35	30	24	12	−3
R. Knee Flexion	7	10	42	66	25	9	17	12	7
R. AnklePlant. Fl.	17	11	−13	0	0	−1	−3	7	16
R. GlenoHum. Fl.	−6	−5	−14	−23	−36	−46	−42	−26	−12
R. Elbow Flexion	41	51	49	33	25	22	23	30	42
R. Wrist Flexion	33	37	36	29	24	26	23	29	31

NOTE 1: The 0 % step phase was not evaluated at $t = 0$ *since the experiment measurement did not start with the appropriate leg-position, thus the one step was evaluated between time* $t = 0.6$ *s and* 1.6 *s*

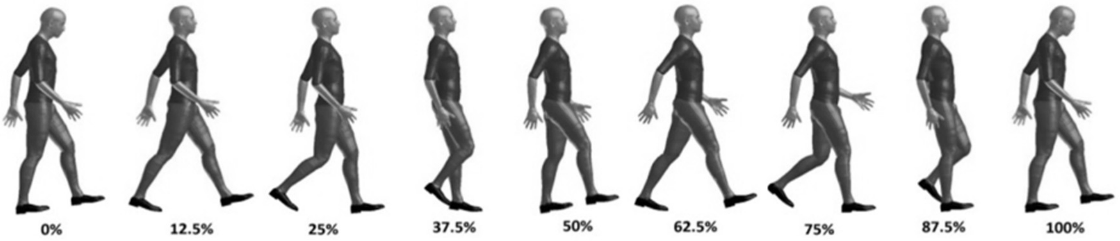


Fig. 3. Human gait phases

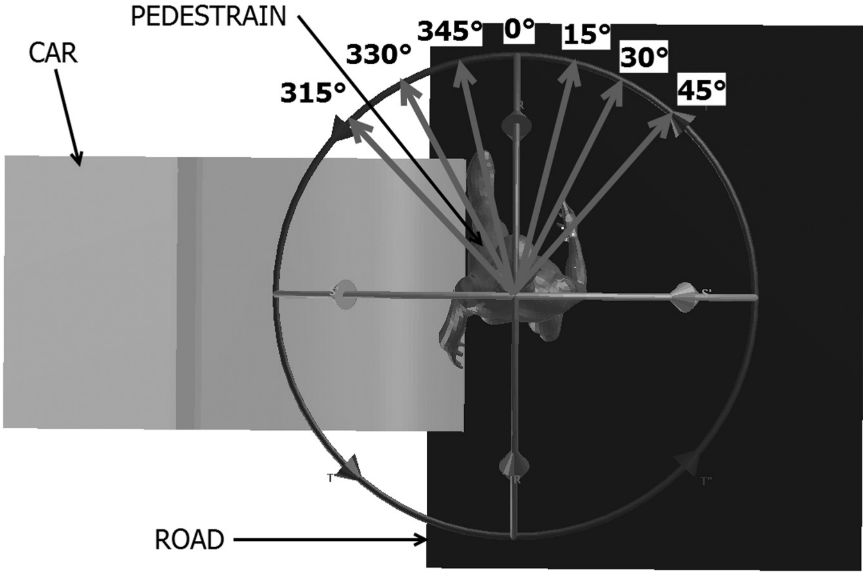


Fig. 4. Pedestrian–car position with denoted turning angles

the step (or double step). Since 0 % and 100 % are identical, only 8 phases are used for further investigation. Each of the eight pedestrian's configurations was eventually turned around its own axis by 15, 30 and 45 degrees either in the direction to the car or away from it. For simplicity, the clockwise angle direction from 0 to 360 degrees is used from now. The meaning of the turning angles is demonstrated in Fig. 4.

For each of the eight step phases, 7 different configurations were obtained by turning the pedestrian sequentially by 0, 15, 30, 45, 315, 330 and 345 degrees. Thus, together there are 56 configurations for the sensitivity analysis of the pedestrian-car collision test in the static case. In other word, zero initial velocities of pedestrian were considered in these configurations. Let us clarify that for the turning angles 15, 30 and 45 degrees, the car impacts the pedestrian from the backward direction, whereas in the case of the turning angles 315, 330 and 345 degrees, the impact occurs from the frontal direction of the pedestrian, see Fig. 4.

3.2. Pedestrian model

The VIRTHUMAN model is a hybrid model that combines the advantages of two main modelling approaches, the deformable elements and rigid body segmentation within the MBS structure. The deformable elements representing external shape of the human body are connected via non-linear springs and dampers to rigid segments. These segments form an open tree structure based on the multibody principle. Particular rigid segments are connected via kinematic joints that

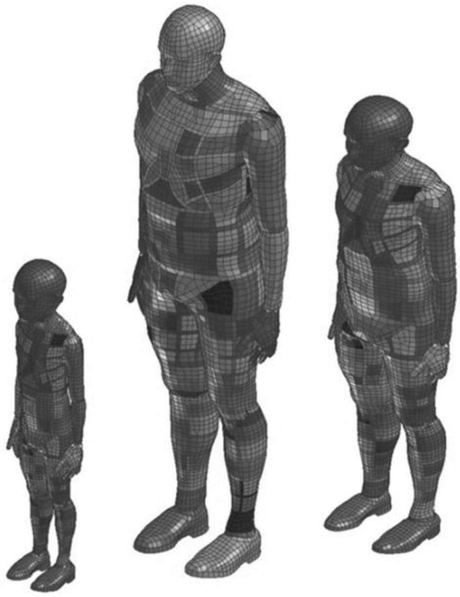


Fig. 5. Scaled VIRTHUMAN model: 6-year-old child, 110 cm, 17 kg (left); 40-year-old male, 190 cm, 104 kg (middle); 70-year-old female, 150 cm, 90 kg (right)

represent real human joints (shoulder, elbow, knee, etc.) or breakable joints for the description of bone fracture. The model was specially validated for pedestrian modelling [23] and [24].

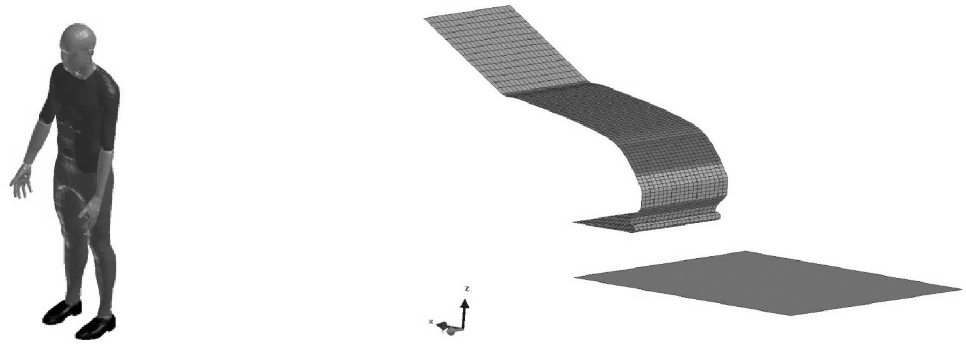
The VIRTHUMAN model is a fully scalable human model that takes into account gender, age, height and weight of a particular subject [9]. The wide set of human anthropometric database [1] is a foundation of automatic scaling algorithm, implemented in the model. With the advantage of scaling process, small children, tiny or tall male (female) or elderly individuals can be considered here. The example of size-variability of VIRTHUMAN model is demonstrated in Fig. 5, where a small child, big male and average female are shown.

The model was fully validated against a large set of validation tests. The full-body tests as well as detailed tests for particular human body segments were performed to ensure the biofidelity of the VIRTHUMAN model [24]. To assess the injury risk probability, an automatic algorithm for evaluation of a specified criterion based on various time-dependent quantities (e.g. contact forces, acceleration, displacement, torques and many others) was developed and implemented in the VIRTHUMAN model [2]. The list of evaluated criterions is available in [23]. The investigated criterion limits are also driven by the pedestrian's age. The evaluation of the considered criterion is indicated by the colouring of particular human body segments based on the EuroNCAP rating [4]. The red color represents poor conditions for the pedestrian injury, orange is marginal, yellow is acceptable and green colour represents good condition for the pedestrian, see Fig. 9 and Tab. 3 and Tab. 4. In this case, the used colour spectra are 4 shades of gray, i.e. light gray for a good condition (originally green), medium-light for acceptable (yellow), medium-dark for marginal (orange) and dark gray for a poor condition (red).

3.3. Representative pedestrian

The VIRTHUMAN model is implemented in the Virtual Performance Solution (VPS) software. Since it is a scalable model, one representative pedestrian was specified for the analysis.

An 18 years-old average (50 % percentile) male with weight equalling to 72 kg and height equalling to 178 cm was chosen, based on the statistical results [11, 21]. The VIRTHUMAN model representing the chosen human in the standing position is displayed in Fig. 6(a).



(a) VIRTHUMAN model – 18 years-old male (72 kg, 178 cm)

(b) Simplified model of car chassis [24]

Fig. 6. Investigated models

3.4. Car and collision description

The goal of this work is to discover a trend of humans injuries depending on initial conditions. Hence the car model was simplified to the car chassis only. The geometry of the front part of the car is defined on the basis of Kerrigan [10] and modelled using the multibody principle, where 4 rigid elements representing external surface of the chassis are connected to a based tree structure with virtual springs and dampers. The model used real characteristics of dampers and springs, which have been fully validated [24]. The simplified model of car hood was successfully used for the kinematic analysis of pedestrian collision [23]. This model of the chassis based on Kerrigan geometry is displayed in Fig. 6(b).

The sensitivity analysis requires a large number of numerical simulations using various initial conditions followed by the prediction of injuries. The main advantage of the hybrid VIRTHUMAN model and the multibody car hood model lies in the generation of solutions within a short computational time, as opposed to the times required by complex finite element models.

3.5. Tested car-to-pedestrian scenario

The car of mass 1 200 kg is moving forward with the initial velocity equalling to 45 km/h and impacts the pedestrian from his left side. Consequently, during the configurations with turning angles of 15, 30 and 45 degrees, the impact is from the backward direction. The contact between car chassis and pedestrian is tuned up to correspond to a real collision scenario. The pedestrian is located narrowly in front of the car, see Fig. 7. The afterwards contact of the pedestrian with the road is not addressed; hence the sufficient duration time is 220 ms.

3.6. Human gait implementation

The effect of the pedestrian motion on the injury prediction rating during car collision was tested here. The modelling of the human gait can be partitioned and modelled in two ways:

- translational motion (velocity) of the pedestrian as a complex unit,
- rotational motion of extremities.

The human gait is represented by the translational motion of the pedestrian in the frontal direction and by the rotational motion of body segments. The rotation and rotational velocities

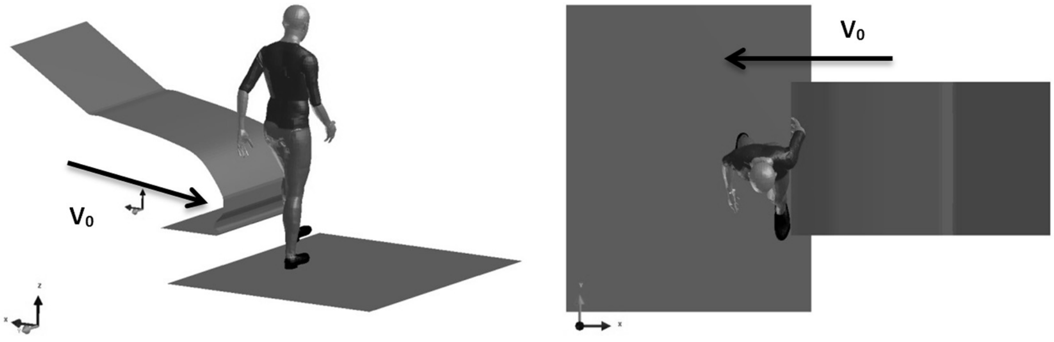


Fig. 7. Crash configuration for the case of 0 % and 0°

of the extremities can influence the kinematics and consequently the dynamics of the crash. The effect of non-zero initial conditions of the rotational velocities on the probability of the injury was tested.

Translational velocity: According to [8], the average speed of normal walk is about 5 km/h. Therefore, the velocities chosen for the analysis were 4 km/h and 6 km/h. These velocities were used as initial velocities of the full human body.

Rotational velocity: Havelková in her experimental testing [7] monitored values of angular velocities of particular joints: shoulders, elbows, hips and knees, for both left and right extremities. These values are plotted in Fig. 8. The dynamics of other human joints is negligible compared to that of the aforementioned joints and hence these joints are not considered here. For further analysis, one phase of the step is specified. The changes of the injury probability for a static case (zero initial velocities) and dynamic case are compared with each other. The step phase of 25 % was chosen, based on the minor differences of the criterion (HIC) among previous, actual and following step phases. Because this section is focused on the effect of initial velocities, not on the effect of various positions of human extremities and thus, the selection with minimal differences of HIC values was chosen as a reasonable criterion. This configuration was extended with non-zero initial conditions; i.e. the translational velocity of the pedestrian and rotational velocity of the selected joints. The values of the angular velocity at the specific step phase of 25 %, evaluated from Fig. 8, are displayed in Table 2. Furthermore the human body was turned by the angle ±15° for the analysis of the dynamic configurations.

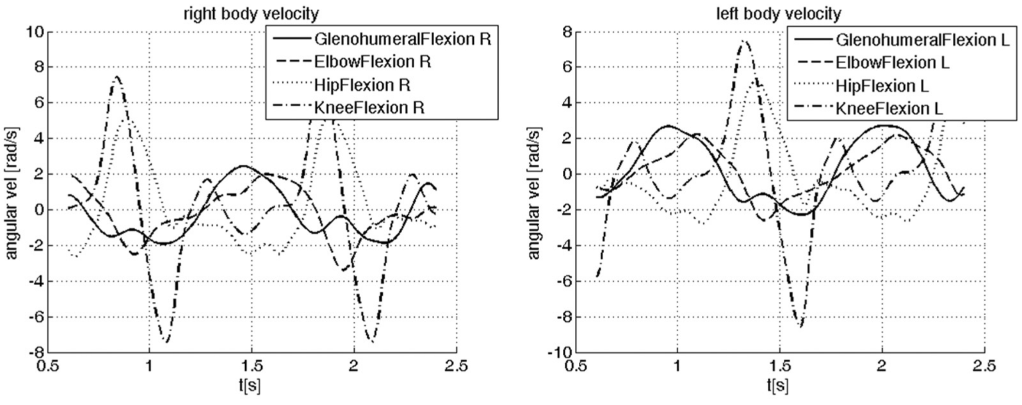


Fig. 8. Angular velocities of selected joints

Table 2. Angular velocities at the 25 % step phase

Joint	**Angular Velocity [rad/s]**
Shoulder Right	-1.37
Elbow Right	-1.52
Hip Right	4.69
Knee Right	7.23
Shoulder Left	-1.73
Elbow Left	-0.55
Hip Left	1.07
Knee Left	-0.23

3.7. Configuration of the parametric study (sensitivity analysis)

The summary of the investigated configurations is presented below:

- Effect of the various step phases and turning of the pedestrian: 8 step phases, in each of them the pedestrian was turned by ±15, 30 and 45 degrees around his own axis (i.e. static case, zero initial velocities, 56 configurations).
- Configuration of the 25 % step phase was tested under non-zero initial velocities:
  - translational velocity of the full human body (4 and 6 km/h),
  - rotational velocities of the selected human joints (for both 4 and 6 km/h translational velocities).

4. Results

Crash simulations of 18 years old average male with the weight 172 cm and height 72 kg was performed in VPS software. The collision with the car of mass 1 200 kg moving with the velocity of 45 km/h was investigated. The injury risk of particular body segments based on EuroNCAP injury rating was evaluated. An example of the injury-coloured (gray-scale) VIRTHUMAN model at the final simulation time is demonstrated in Fig. 9. Here, the light gray colour represents good conditions of survivability, medium-light gray for acceptable conditions, medium-dark gray for marginal conditions and dark gray indicates poor survivability conditions.

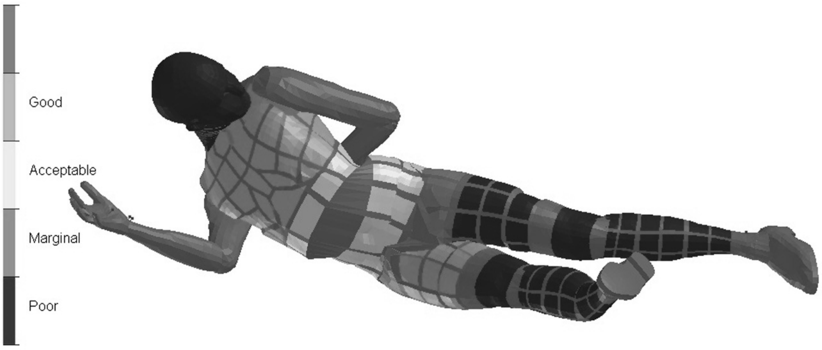


Fig. 9. VIRTHUMAN automatic injury risk evaluation

4.1. Static cases (zero initial velocities)

The kinematics of the VIRTHUMAN model during the collision scenario is depicted in the set of Fig. 10. The basic configuration of the 0 % step phase and rotation $R = 0^\circ$ is presented here at several chosen time instants. The time interval is linearly distributed with a time step equal to 20 ms, the start $t = 0$ until the final time $t = 220\,\text{ms}$.

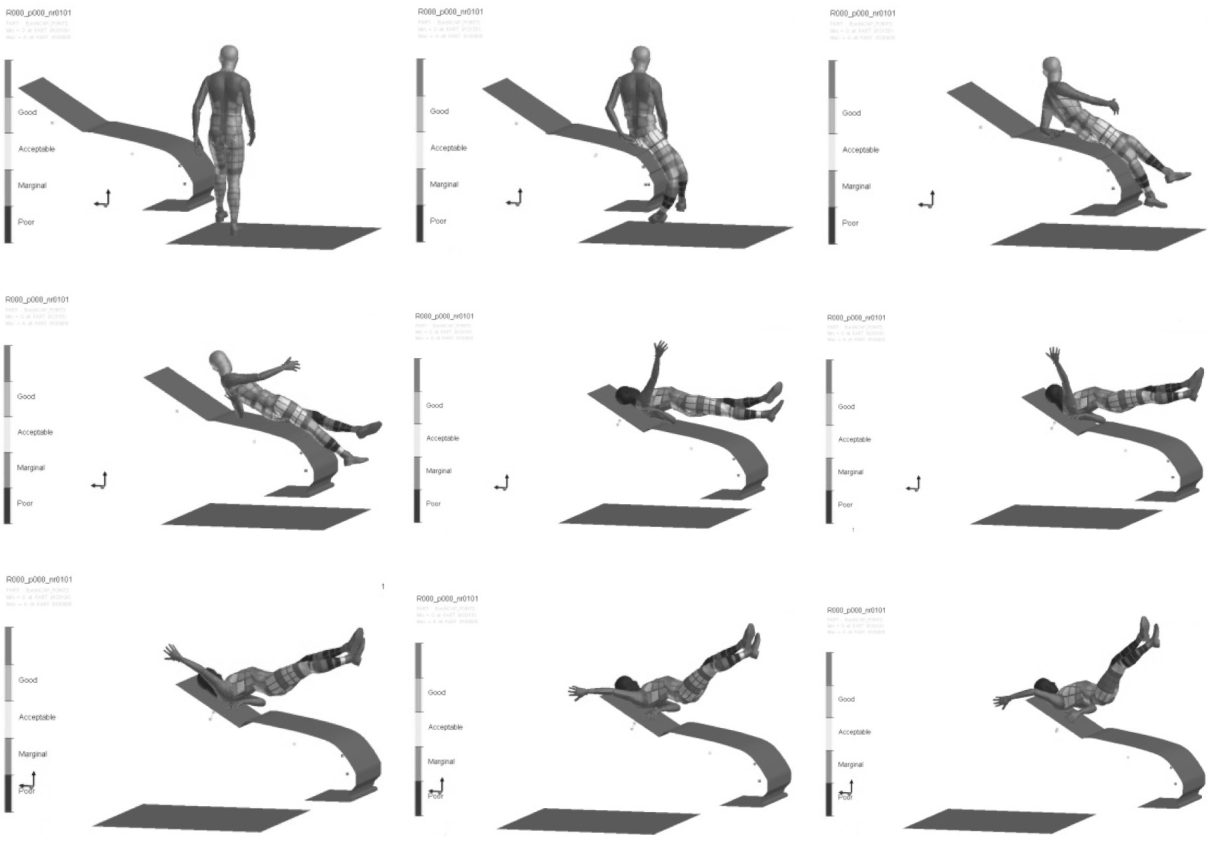


Fig. 10. Pedestrian's motion and segments coloured on the basis of EuroNCAP injury risk rating

Injury risk is evaluated in each time step of the simulation and particular body segments are marked with appropriate colour based on the injury risk evaluation defined above. At the final time, the maximum values across all the frames are used for the injury risk evaluation. The detailed descriptions of the evaluated criteria are available in [23]. In Table 3, a cell keeps the colour of the defined injury risk [4]. The head cell contains also the value of the Head Injury Criterion (later referred to as HIC36) [24]. The results of the sensitivity analysis listed in table represent the most critical results achieved during the collision. Since the evaluated injury criterion is not just a single value, but a complex of set of criterions, it is not possible to express them within this paper. For a detailed description, see [2, 23, 24].

Table 3. Results of the sensitivity analysis, static case, various step phases and turning angles

Step phase [p%]	Rotation [R°]	Head	Neck	Chest	Abdomen	Pelvis	Femur		Knee		Tibia	
							Right	Left	Right	Left	Right	Left
0	0	▓ 1509	▓	░	□	░	▒	▒	░	▓	▓	▓
	15	▓ 1400	▓	░	░	□	░	▓	░	▓	▓	▓
	30	▓ 1220	▓	░	░	□	░	▓	░	▓	▒	▓
	45	▓ 1832	▓	□	▒	□	░	░	□	▒	▓	▓
	315	▓ 1204	░	▒	□	□	▓	▒	▓	▒	▒	▓
	330	▓ 1147	□	░	□	□	▒	▒	▒	░	▓	▒
	345	▓ 1415	░	▒	□	□	▒	▓	▓	▒	▓	▒
12.5	0	▒ 990	▓	░	░	░	□	▒	□	▒	▒	▓
	15	▓ 1241	▓	░	░	░	□	▓	□	▓	▓	▓
	30	▓ 1926	▓	□	□	░	▒	▓	▒	▓	▒	▒
	45	▓ 1664	▓	□	□	□	░	▒	□	▓	▓	▓
	315	▓ 1137	▓	▒	□	□	▒	▓	░	▓	▓	▓
	330	▒ 941	░	░	░	□	▓	▓	▒	□	▓	▒
	345	▒ 976	▓	▒	░	▒	□	▓	░	░	▒	▒
25	0	▓ 1176	▓	□	░	▒	□	▒	▓	▒	▓	▓
	15	▓ 1579	▓	□	░	▒	□	▓	▒	▓	░	▓
	30	▓ 2013	▓	□	░	□	▒	▓	▓	░	▒	░
	45	▓ 2168	▓	□	▒	░	▒	▒	▓	▒	▓	▒
	315	▓ 1234	▓	░	□	□	▒	▓	▓	▓	▒	▒
	330	▒ 937	▓	░	░	░	▓	▓	▓	░	▒	▓
	345	▓ 1033	▓	░	□	▒	░	▒	▓	▒	▓	▓
37.5	0	▓ 1220	▓	░	□	░	□	▓	▓	□	▓	▒
	15	▓ 1066	▓	□	□	░	□	▓	▒	▓	▓	▒
	30	▓ 1609	▓	□	□	□	░	▓	▓	▓	▒	▒
	45	▓ 2375	▓	□	□	□	□	▒	▓	▒	░	▒
	315	▓ 2143	▓	□	□	□	▓	▓	□	▒	▒	▒
	330	▓ 1465	▓	▒	□	□	▓	▓	□	▒	▓	▓
	345	▒ 960	▓	▒	□	□	▓	▓	▓	▓	▒	▓

Table 3. *Continued*

Step phase [p%]	Rotation [R°]	Head	Neck	Chest	Abdomen	Pelvis	Femur		Knee		Tibia	
							Right	Left	Right	Left	Right	Left
50	0	462	▓	▒	□	□	▒	▓	▒	▓	▓	▓
	15	601	▒	▒	□	░	▓	▓	░	▓	▓	▓
	30	973	▓	□	□	□	▓	▓	▒	□	▓	▓
	45	1524	▓	□	□	□	□	▓	▓	▒	▓	▓
	315	1763	░	□	□	□	▓	▒	□	▓	▒	▓
	330	1037	▓	□	□	□	▓	▓	▓	▓	▒	▓
	345	730	▓	░	□	□	░	▓	□	▓	▒	▒
62.5	0	948	▓	▒	□	▒	□	▒	□	▓	▓	▒
	15	1036	▓	▒	□	░	▓	▓	░	▓	▓	▒
	30	949	▓	░	□	░	▓	▓	░	▒	▓	▒
	45	1015	▓	□	□	░	░	▓	▒	□	▓	▓
	315	1392	░	░	□	□	▓	▓	░	▓	░	▓
	330	1126	▒	▒	□	□	▒	▓	□	▓	▓	▓
	345	910	▓	▒	□	░	░	▒	□	▓	▓	▒
75	0	1067	▓	▒	□	□	▓	▒	▒	▒	▓	▒
	15	1071	▓	▒	□	□	▓	▓	▓	▒	▓	░
	30	1123	▓	░	□	░	▒	▓	▓	▓	▓	░
	45	1835	▓	□	□	□	▓	□	▓	▓	▓	▒
	315	1264	░	░	□	□	▒	▓	░	□	▓	▒
	330	851	▓	░	□	□	▒	▓	░	□	▓	░
	345	1034	▓	▒	□	░	▒	░	▒	▒	▓	▒
87.5	0	1307	▓	□	□	□	░	▒	▓	□	▓	▓
	15	1545	▓	□	□	□	▒	▓	░	▓	▓	▓
	30	1620	▓	□	□	□	▒	▓	□	▓	░	▒
	45	1541	▓	□	□	□	▒	▓	░	▓	▒	▒
	315	1082	▓	□	░	□	▓	▒	▓	□	▓	▒
	330	871	▓	□	▒	□	▓	▓	▓	□	▓	▓
	345	780	▓	□	□	□	▒	▒	▒	□	▓	▓

4.2. Dynamic case (non-zero initial velocities)

Translational velocities: Figs. 11, 12 and 13 show the motion of the pedestrian for three different initial translational velocities: 0 km/h (light gray), 4 km/h (medium gray) and 6 km/h (dark gray), respectively, and zero initial angular velocities. The results of the 25 % step phase configuration for the turning angles 0, 45 and 315 (−45) degrees, respectively are plotted.

Table 4 summarises the results of the injury risk for the 25 % step phase in the static (zero initial velocity) and dynamic (translational and rotational initial velocities) cases. The configurations with translational velocity only and both, translational and angular velocities are presented here. Again the head cells contain the value of HIC36 criterion.

Table 4. Results of the simulation with non-zero initial velocities, 25 % step phase and turning angle ±15°

Step phase [p%] /Turning angle [R°]	Initial velocity [km/h]	Head	Neck	Chest	Abdomen	Pelvis	Femur		Knee		Tibia	
							Right	Left	Right	Left	Right	Left
p25/0° Zero angular velocities	0	1167 ▓	▓	□	░	▒	□	▒	▓	▓	▓	▓
	4	1157 ▓	▓	□	░	▒	□	▒	▓	▓	▓	▓
	6	1146 ▓	▓	□	░	▒	□	▓	▓	▓	▓	▓
p25/0° Non-zero angular velocities	0	1269 ▓	▓	□	░	▒	□	▒	▓	▓	▓	▓
	4	1131 ▓	▓	□	░	▒	□	▒	▓	▓	▓	▓
	6	1170 ▓	▓	□	░	░	□	▓	▓	▓	▓	▓
p25/15° Zero angular velocities	0	1665 ▓	▓	□	□	▒	▒	▓	▓	▓	░	▓
	4	1461 ▓	▓	□	□	▒	□	▓	▓	▓	▒	▓
	6	1453 ▓	▓	□	□	▒	▒	▓	▓	▓	▒	▓
p25/15° Non-zero angular velocities	0	1593 ▓	▓	□	░	▒	□	▓	▓	▓	▒	▓
	4	1433 ▓	▓	▒	□	▒	□	▓	▓	▓	▒	▓
	6	1440 ▓	▓	▒	░	▒	□	▓	▓	▓	▒	▓
p25/345° Zero angular velocities	0	1034 ▓	▓	░	□	▒	░	▒	▓	▓	▓	▓
	4	1020 ▓	▓	░	░	░	▒	▓	▓	▓	▓	▒
	6	996 ▒	▓	░	□	░	▒	▓	▓	▓	▓	▒
p25/345° Non-zero angular velocities	0	1072 ▓	▓	░	░	░	▒	▒	▓	▓	▓	▒
	4	1038 ▓	□	░	░	░	▒	▓	▓	▓	▓	▓
	6	971 ▒	▓	░	░	░	▒	▓	▓	▓	▓	▒

$\mathbf{R} = 0^\circ$

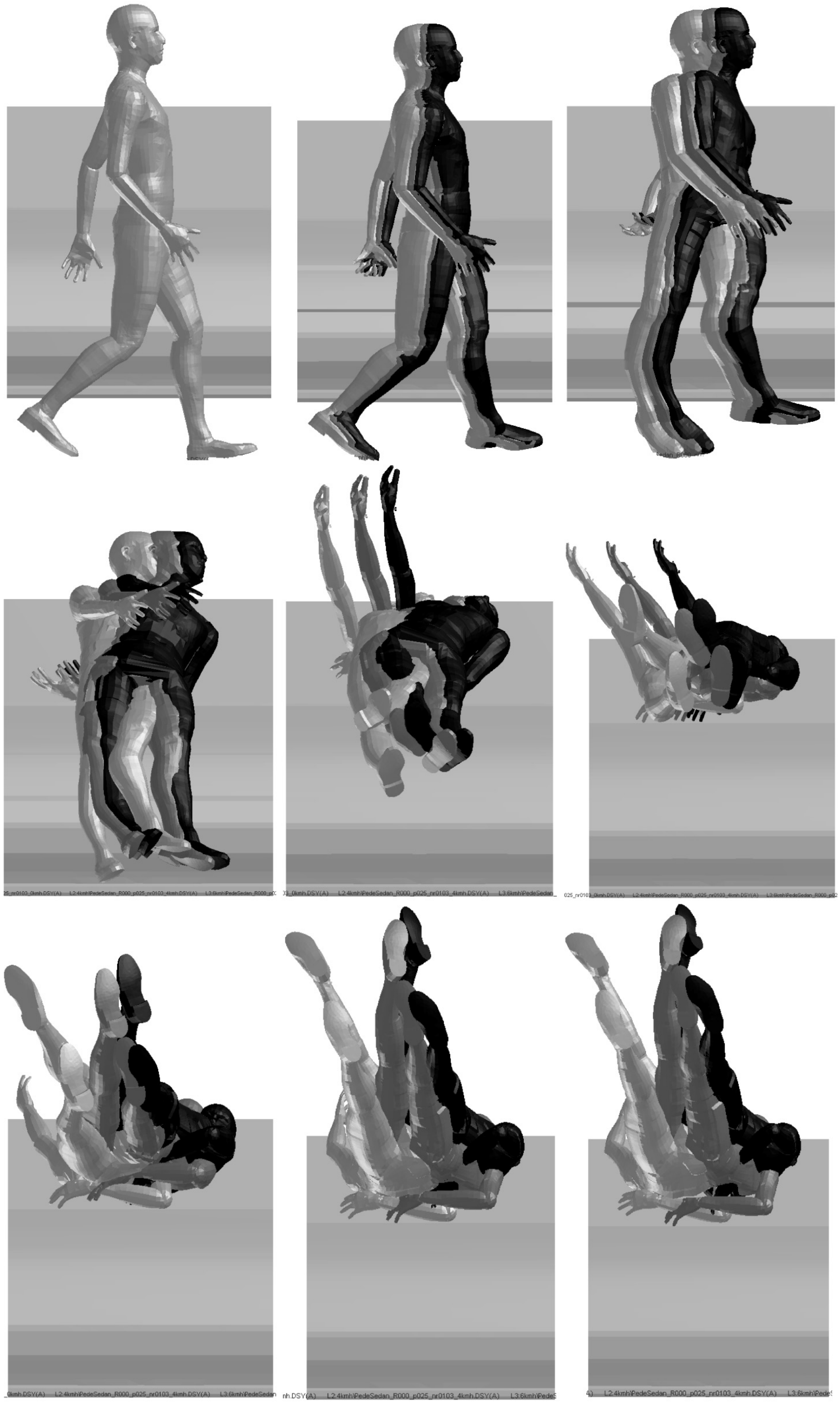


Fig. 11. Crash simulation of the 25 % step phase with turning angle of 0°

$\mathbf{R} = 45^\circ$

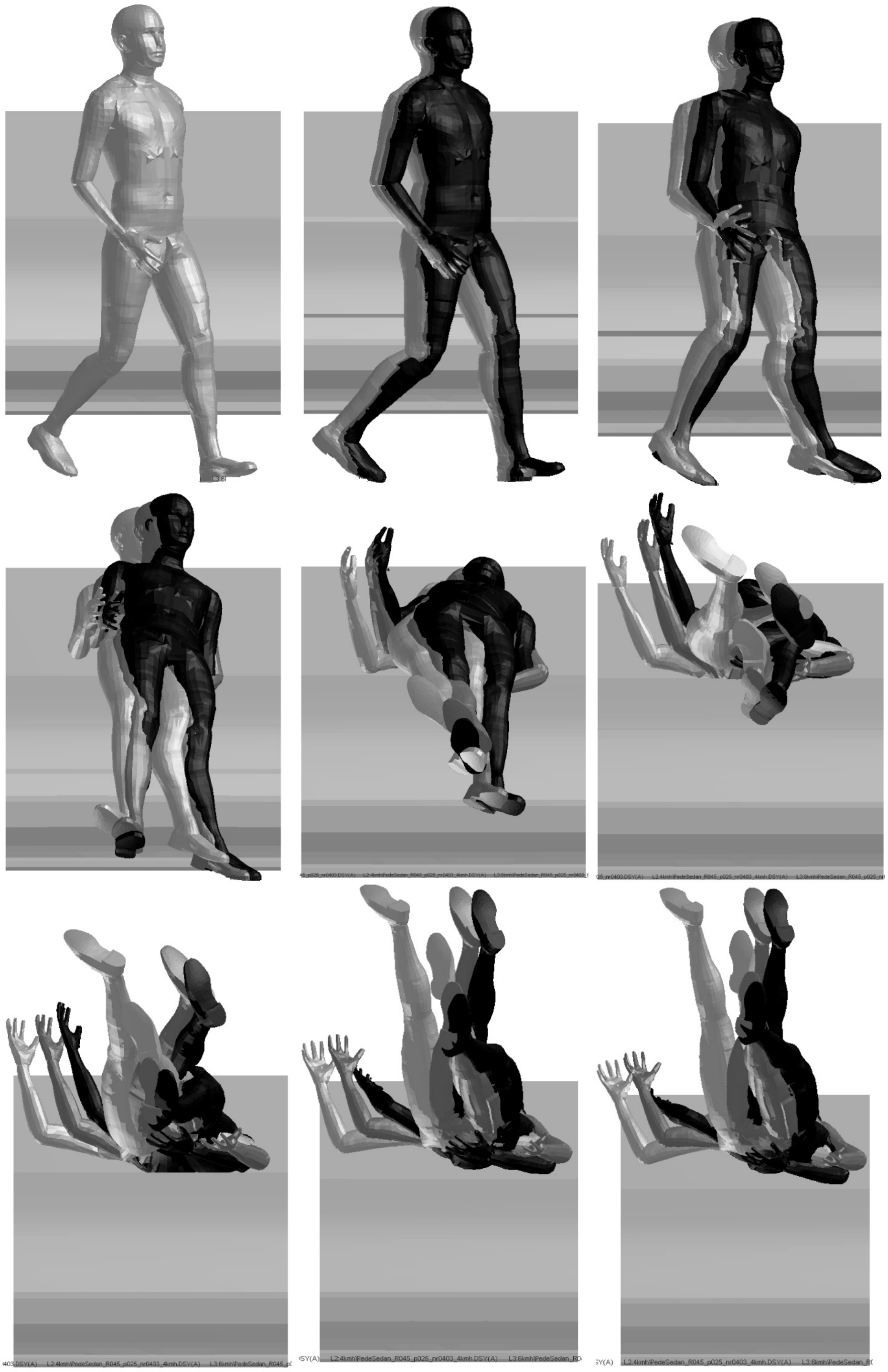


Fig. 12. Crash simulation of the 25 % step phase with turning angle of 45°

$\mathbf{R} = 315^\circ$

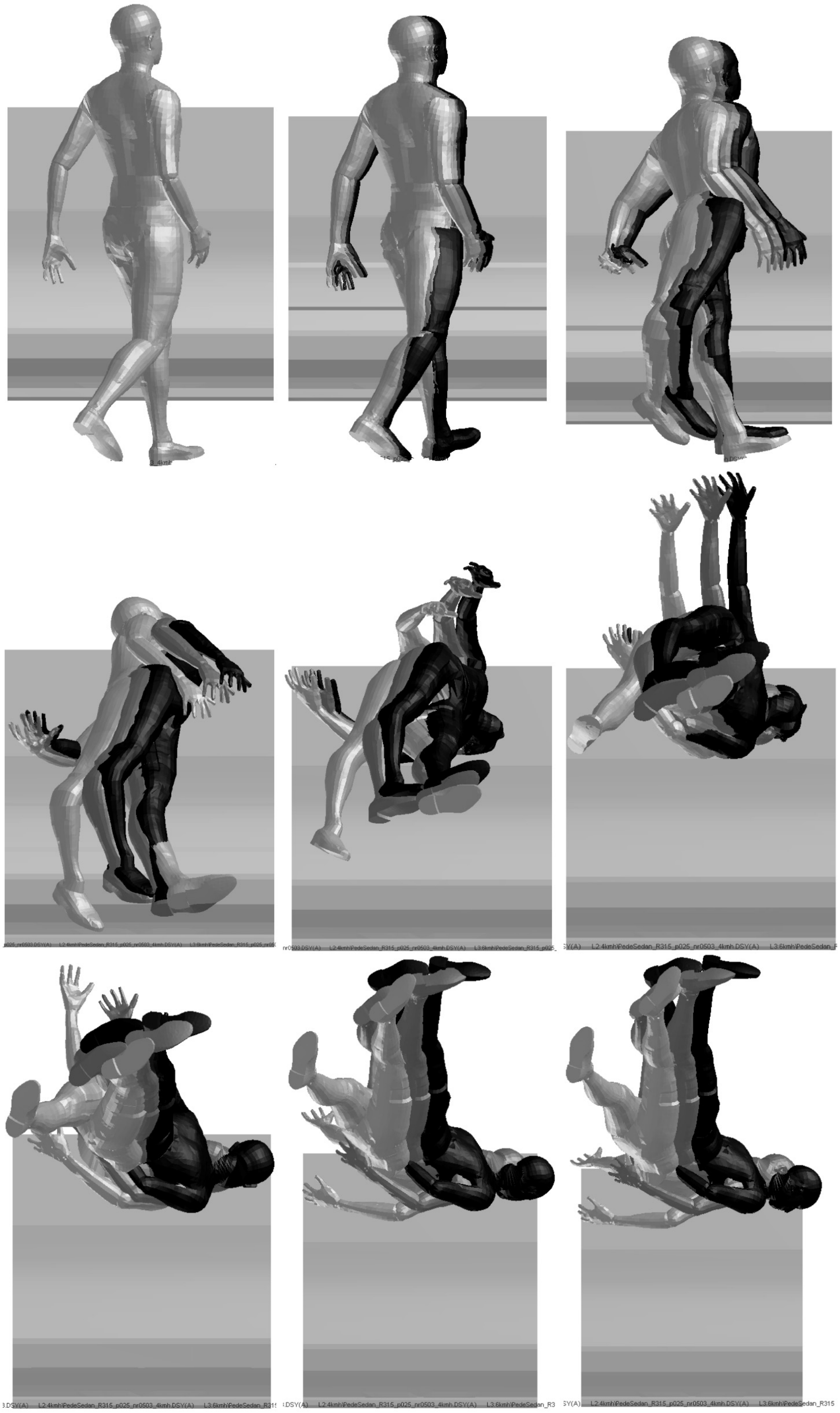


Fig. 13. Crash simulation of the 25 % step phase with turning angle of 315°

5. Discussion

5.1. Modelling

This paper is focused on the modelling and simulation of the car to pedestrian crash scenario. The authors are focused on one specific collision. They analyse the effect of initial pedestrian's postures on the kinematics of the collision (primary impact, after impact motion and secondary impact with the ground), and consequently on the injury risk sustained by the pedestrian. This paper employs the virtual human body model, VIRTHUMAN, for the pedestrian modelling. To reduce the computational costs of the study, the car was simplified and reduced to the frontal part only, modeled via four rigid bodies connected with translation joints and non-linear springs and dampers. Since the emphasis is placed on the prediction of the injury trend as a function of gait phases rather than absolute values, this simplification is acceptable. Unfortunately, for lack of the verification data, the results cannot be compared with a real accident.

Li et al. in their work [12] discussed the effect of gait stances on the injury of the leg (struck and non-struck leg) in the crash scenario, where the vehicle at 40 km/h hits the pedestrian. The results conclude that a gait phase significantly affects the stress of the lower extremities (Von Mises stress of the bone, bending moment and stress of the ligaments). The VIRTHUMAN model does not consider the bone as a single structure and thus, a direct comparison of results cannot be carried out. However, the injury prediction calculated in this study are not in conflict with the published results. The leg injuries (tibia, femur, knee) vary significantly through the gait phases. The differences are caused mainly by the shifting of the leg (loaded and unloaded leg) as well as by the bending angle (knee, hip) changing the impacting area on the leg. The sensitivity analysis correlates with the results of the previous study by Li et al. [12].

5.2. Static case (zero initial velocity)

The sensitivity analysis of the various initial conditions of the static case car-to-pedestrian collision with the car initial velocity equalling to 45 km/h can be summarised as follows: The injury criteria of the head and the neck imply high probability of injury risk (poor survival conditions), in most configurations. The chest, abdomen and pelvis injury criteria imply marginal or acceptable conditions. The lower extremities exhibit direct impact with the car, which consequently results in poor survivability conditions. A detailed discussion of particular body segments is presented below.

It is indisputable that the simplified bonnet of the car does not precisely approximate a real car. The present study is more focused on the effect of gait stances and extremities posture rather than on the effect of contact area on a real car bonnet, which can also affect the injury and collision process. In real cars, there is a system of reinforcement behind the bonnet or there are stiffer parts close to the side of the bonnet that might change the collision scenario and consequently the results. However, these factors are not the objective of this study.

Head: The criterion HIC36 (Head Injury Criterion at time interval 36 ms) is a commonly used criterion for the evaluation of head acceleration. For values over the value overreached the critical limit of 1 000 [–], it implies low survival probability. In this study, the critical value was crossed in the most cases (83 %). Two configurations ($p = 50$ %, $R = 0^\circ$ and $p = 50$ %, $R = 15^\circ$) demonstrate HIC36 values below the limit of any significant (acceptable) injury risk. During these particular configurations, the first impact of the pedestrian with the car occurred at the elbow. This semi-contact dissipates the majority of the impact energy and consequently the head is supported by the shoulder before it collides with the windshield. This scenario results in a low acceleration level of the head. The results show positive effect of the posture of the upper extremities on the injury risk of the head. On the other hand, only a small difference in the initial position can result in significantly different values. Such results seem to be likely an exception rather than a real crash stance.

There is regularity in the turning angles 330 or/and 340 degrees resulting in lower HIC36 values (acceptable of marginal injury risk conditions). The increase in HIC values is caused mostly by the upper extremities initial contact, which can support or particularly protect the head.

The effect of elbow-dissipation usually occurred in the backward direction of the impact, and this can also cause the decrease in HIC36 values.

Neck: Similarly to the head, the neck also exposed the poor or marginal injury risk conditions in most scenarios. There is no significant trend of neck injuries through the step phases or turning angles.

Chest: The chest injury probability is not so critical compared to the head or neck. The only meaningful trend is a lower injury risk when the turning angle equals 30 and 45 degrees.

Abdomen and pelvis: The injury risk of the abdomen and pelvis remains in good conditions in most cases. Only few configurations cause a noticeable injury (acceptable or marginal). There is no significant trend in the injury change.

Femur and knee: The lower extremities injury is tightly connected with the pedestrian's impact side. The higher injury risk appears at the left leg, since the car impacts pedestrian from his left side.

Tibia: The injury risk results mainly in poor conditions. Some differences can be seen between the left and right tibias, but they are not as significant as in the femur case. A detailed analysis of the collision, can lead to the results in the following trend: "If the car impacts the lifted (unloaded) leg, the injury risk is lower compared to the standing (loaded) leg."

Upper extremities: The upper extremities injury risk is not considered in the VIRTHUMAN as well as in the EuroNCAP rating. Their injuries are usually less serious than that of other body parts and do not endanger the pedestrian life.

5.3. Dynamics case (non-zero initial velocities)

The effect of joint angular velocities on the dynamics of the pedestrian and consequently on the injury probability was tested. The aim was to find out, whether the pedestrian's motion (motion of the full body and relative motion of the extremities) can significantly affect the crash process and should be considered in further studies, or can remain neglected. In some cases, there is a positive/negative change of injury sustained (see p25 %, R15° – right femur or pelvis p25 %, R15°). On the other hand, there are configurations with no significant variance in injury prediction. Generally, there is no global trend of increasing or decreasing the injury probability with the considered initial angular velocities. The most critical parts, head and legs, remained significantly injured. Thus, based on the performed simulations, one can conclude that there is no significant effect of the angular velocities on the injury risk predictions. Hence, for the case of normal walk (speed about 5 km/h) angular velocities of the upper and lower extremities do not affect the after impact motion nor afterwards injury prediction. Thus it can remain neglected in simulations of car-to-pedestrian collisions, when the pedestrian moves with a normal average walk. However, the definition of translational velocities generally modified (in this particular case decreased) the level of injuries for the simplified car model. Moreover, it can relocalise the contact site on the bonnet, which can significantly change the results when a real car including all bonnet reinforcements is considered. In our simplified car model (i.e. chassis only), which is laterally symmetric and contains no rigid reinforcements, any change of contact site from left to right will not influence the results (injury risk).

5.4. Limitation of this study and further work

Present study has several limitations as it only investigates special cases. Firstly, the car was simplified to a symmetric chassis only, modelled as a multibody structure containing four rigid segments with a deformable constraint. Despite the car simplification, the model was used in previous studies and was validated for the present application. The rigid elements are connected with non-linear springs and dampers, which have mechanical characteristics based on real data. For further work, a fully deformable model of a real car will be tested to expand the results of this sensitivity analysis.

Secondly, there was only one tested car velocity equalling 45 km/h. Moreover, the pedestrian motion was analysed during normal walk speed (4–6 km/h) only. The selected pedestrian model, an average 18 years-old male (72 kg, 178 cm), was chosen based on the statistical results and with respect to other adjacent studies. The authors have already at their disposal results from simulations carried out for various pedestrian's weights and heights. These show us that, these inputs are crucial parameters affecting the injury. Thus the variation of the pedestrian size and car initial velocity seem to be a challenge for further work.

6. Conclusion

The paper presented results of pedestrian injury during collision with a car and the dependence of injuries on the various initial conditions of the human. The shape of the car was simplified to a symmetric chassis only. Rigid plates connected via deformable spring and damper elements to the basic kinematic tree structure were used for the approximation of the external shape of the car. The fully validated VIRTHUMAN model under the VPS software was applied for the modelling of the pedestrian and the simulation of the collision scenario. The sensitivity analysis of the various phases of the human gait and their effect on injury risk probability was presented. The representative 50th percentile male VIRTHUMAN model (18 years old, 178 cm and 82 kg) was set-up for various step phases when crossing the road and each of the step phases was then turned by 15, 30 and 45 degrees in the direction to the car or away from it. The car was moving in the frontal direction with the initial velocity equal to 45 km/h and impacting the pedestrian from his left side. Together, there were 56 simulations for the sensitivity analysis of the static collision case. The injury risk was evaluated based on EuroNCAP injury risk rating.

The dynamic study considered non-zero initial velocities of the pedestrian (translational and rotational). The human body in the chosen configuration (step phase of 25 %) was eventually turned by the angle ±15°. The initial velocities of 0 km/h, 4 km/h and 6 km/h of the full body as well as angular velocities of the extremities were defined on the VIRTHUMAN model. The simulation was performed with the definition of translational velocity only and with both, translational and rotational velocities, to examine the influence of rotational velocities. The probabilities of the injury risk for the various body segments were compared with each other.

This paper dealt with the sensitivity analysis of the car-to-pedestrian collision. The results confirmed a significant effect of the initial position (step phases and turning angle) on the crash process and the injury risk. The initial position of the extremities affected the kinematics and dynamics of the collision. In some cases, the initial contact of the pedestrian with the bonnet occurred through the elbow that absorbed the majority of the impact energy and resulted in a decrease of HIC criterion.

The effect of the translational velocity only was not of primary interest in this paper, since the bonnet was modeled as axisymmetric with no reinforcements and a re-localisation of the impact site from the left to the right (and vice versa) does not cause any significant changes. On the other hand, the translational velocity of the full human body influences the pedestrian's motion. The translational velocities were also used for the monitoring of the effect of angular velocities. Moreover, this study implied that the angular velocities of the human extremities do not affect the dynamics of the crash scenario, nor the probability of injuries in the case of a normal walk. On the other hand, the initial position and translational velocities of the pedestrian with respect to the car affects the dynamic of the collision and as such should be considered during the modelling. For further research, the sensitivity analysis can be extended with a FEM model of a complete car (not only of the simplified model containing four rigid segments). Various pedestrian velocities, representing a fast running pedestrian as well as a variation of the vehicle velocity can be taken into account and enable a more complex analysis of the car-to-pedestrian collision.

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