2018 IEEE Intelligent Vehicles Symposium (IV)
Changshu, Suzhou, China, June 26-30, 2018

A Virtual Reality based Approach for Researching Pedestrian to Vehicle Collisions

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***Abstract*—This paper presents a novel approach for the research on pedestrian to vehicle collisions in a realistic virtual environment. The reactions and crossing behavior of test subjects were examined using a pedestrian simulator, consisting of a full body wireless motion capture system and virtual reality glasses in which a virtual traffic environment is displayed. The crossing behavior of 23 participants was investigated in 9 different virtual traffic scenarios in which the velocities of the approaching vehicles, driving direction and traffic density is varied. In case of a virtual collision the body posture and impact position at the vehicle front was captured. Based on the variety of captured body postures at time of collision, typical pedestrian accident postures can be determined. The data was used as input to investigate the influence of the body posture on kinematics of the pedestrian during a car-pedestrian-impact using the Finite-Element Method (FEM). Therefore, the current standard SAE pedestrian test posture was compared to a non-standard posture which was recorded using the pedestrian simulator. In summary, the virtual reality based approach can be used for reproducible research on pedestrian to vehicle collisions, pre-collision pedestrian behavior and reactions and the optimization of pedestrian test models.**

***Index Terms*—VR testing, pedestrian simulator, pedestrian behavior, pedestrian to vehicle interaction, FEM simulation.**

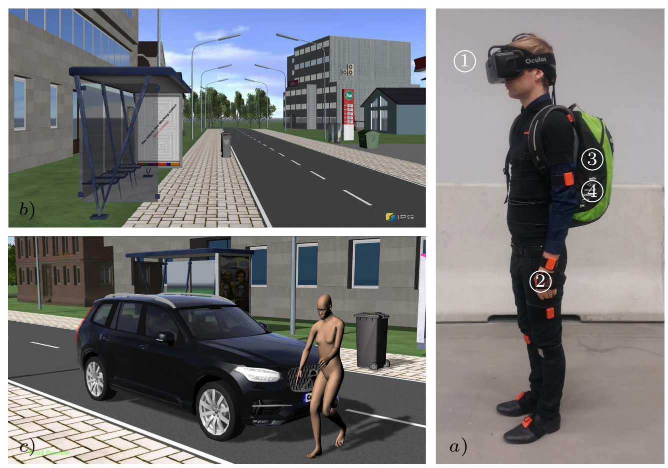


Fig. 1: a) Setup of the pedestrian simulator: (1) VR-glasses, (2) 17 small and lightweight inertial motion capture sensors attached to the test subject (3) motion data receiver (4) notebook with simulation software b) visual feedback to VR-glasses: ego perspective c) third person perspective: virtual pedestrian to vehicle collision

I. Introduction

While vehicle passengers are protected by the vehicle chassis and cyclists and motor cyclists by a helmet, pedestrian traffic participants usually wear no protection at all. According to the Federal Statistical Office [1], around one in three traffic deaths 2016 in urban area in Germany were based on pedestrian to vehicle collisions. In contrast, less than a half percent of all vehicle collisions in urban areas without the involvement of unprotected road users, are fatal accidents.

Globally, a total number of approximately 275 000 pedestrians die per year in traffic accidents [2]. In order to reduce this number, active and passive pedestrian safety systems must be constantly further developed and tested.

A. Motivation

Pedestrian safety systems can be devided into active and passive safety systems. While active systems aim to prevent a collision, passive systems are designed to mitigate the consequences when a collision can not be avoided.

Active systems, like automatic emergency brake systems, are based on environmental sensors like radar, laser scanner and camera. Although active systems will help to reduce the total number of collisions, it can not be expected that all collisions will be entirely prevented, especially at bad weather conditions [3] [4], or if the pedestrian is darting from behind an obstacle onto the road. Head and traumatic brain injuries are the most common cause of death in pedestrian collisions [5]. Therefore, passive pedestrian safety systems, like an optimized vehicle front structure or an active pedestrian hood [6] will still be mandatory in future. The design of the vehicle front and used materials have a big influence on the head impact time. Simulating a car-pedestrian-impact with a numerical model of the vehicle and a FE human body model (HBM) has thereby the potential to optimize active and passive safety systems [7]. However, to obtain meaningful results, realistic pedestrian postures at the time of collision are required.

B. Research Objective

Passive safety systems, which increase the chance of survival of unprotected road users in case of a collision, can be testet by virtual full body car-pedestrian interactions [7]. For the improvement of passive safety systems, crash simulations with vehicle and human body finite element (FE) models are performed [8]. With FE-simulations the investigation of body kinematics and injury mechanism is possible based on a detailed human model through crash simulations of various pedestrian to vehicle impact situations [9]. For the validation of the biofidely of FE-models, whole body tests with post mortem human subjects (PMHS) are performed. Based on this tests the severity and the type of injuries are investigated and compared with the results from simulations with FE-models in pedestrian-vehicle interactions [10]. The PMHS test posture proposed in [11] is based on analysis of pedestrian crash data studies, multi body simulations and literature review.

[12] shows that 55% of pedestrians were walking and 38% were running or jogging at time of collision. Furthermore, in [12] it is reported, that the pedestrian reaction, respectively the planned physical maneuver to escape the arriving vehicle just before the imminent collision is unknown. Different studies [13] [14] show that the body posture at time of collision plays an important role regarding whole body kinematics and head impact time in car-pedestrian interactions. [13] showed in a study the remarkable influence of different gait stance to upper body kinematics in car-pedestrian interaction simulations. In order to improve simulation results, realistic body postures at time of collision are required. The VR based pedestrian simulator, presented in [15], enables the research of pedestrian crossing behavior and risk acceptance in a reproducible and safe environment. Based on this approach, the motion capture data of test subjects during the virtual road crossing can be extracted.

Focus of this paper is the research on pedestrian postures at time of collision based on the approach presented in [15]. Therefore, a VR based study with the pedestrian simulator and 23 subjects was conducted. Each subject was equipped with the pedestrian simulator, consisting of VR glasses, a human motion capture system and a simulation software and was asked to virtually cross a street in 9 different traffic scenarios. In case of a virtual collision the body posture and the point of collision at the vehicle were captured. Based on the results, one representative body posture was selected. Comparative FE-simulations were performed, with the FE HBM positioned, on the one hand, according to the current standard SAE pedestrian posture proposed in [16] and, on the other hand, according to the selected representative body posture from this study. Objective was to investigate the influence of the pedestrian posture on impact kinematics. Furthermore, an average pedestrian collision posture was determined based on average joint angles at all captured virtual collisions.

II. Related Work

A. Pedestrian Simulator

There are several systems and approaches that aim to enable the research on pedestrian behavior in a safe and realistic environment.

In [17] the virtual environment is projected by 3D projectors on three walls as well as on the ground. The orientation and transition of the head is captured by a OptiTrack motion capture system, based on reflective markers on a helmet. The possible motion area is restricted by the size of the room which is 3 m wide and 4.3 m long.

In [18] the pedestrian simulator is based on a treadmill which is surrounded by three screens. One front screen, one right screen and one back screen. In order to move in the virtual environment, participants walk on the center placed treadmill. The motion of the head, neck, waist and both knees is captured by a 6D motion capture system. However, the system enables only linear motion.

In [19] the pedestrian simulator is based on an optical motion capture system and VR-glasses. The body movement is tracked by a setup of multiple infrared cameras and 39 reflective optical markers which are attached to the participants body. However, the possible motion area is restricted by the size of the room where the cameras are installed and the maximum range of the infrared system. The manufacturer of the used motion capture system recommends a maximum room size of 5 by 8 meters [20].

B. Initial Positioning of PMHS

Full-scale tests carried out in [21] and [10] refer to the positioning guideline in SAE J2782 [16].

This guideline is based on the proposed experimental setup and initial positioning of the extremities published in [11] which is based on literature review, multi-body modeling and epidemiological studies. The PMHS initial body orientation is positioned laterally to the oncoming experimental vehicle.

This orientation is proposed based on insights from PCDS database, which contains 521 pedestrian collisions [22]. Based on the database 75% of the pedestrian had their body orientation laterally to the vehicle at time of collision.

Furthermore, the PMHS is positioned in a mid-gait stance, with the right foot back and the left foot forward, both flat on the ground, which is also based on a PCDS analysis, reporting that 55% of the pedestrians motion pattern at time of collision was walking. The set PMHS step width varies from 35 cm to 60 cm and depends on the subjects height, weight, age and gender.

Based on [11] unfixed upper extremities lead to spinning arms, which rotate from test to test in different directions and thus influence the repeatability and comparability of PMHS tests. Therefore, the upper extremities of the PMHS were positioned with both hands bound at crossed wrists in front of the abdomen as can be seen in Fig. 5.

III. Materials and Methods

A. Pedestrian Simulator

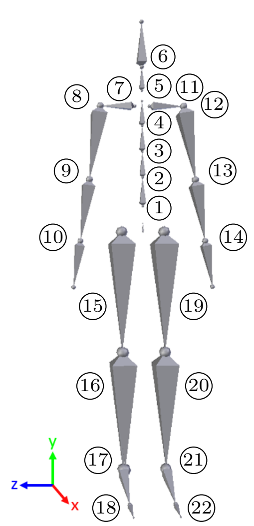
The study is conducted in a virtual environment through the use of a specially developed pedestrian simulator, which allows participants to move in a defined virtual traffic scenario.

1) System Components:

a) Motion Capture System: The selected Xsens full body motion capture system enables the recording of human movements. It consists of 17 small and lightweight intertial sensors, which are able to measure 3D acceleration through linear accelerometers, angular velocity by 3D rate gyroscopes, the magnetic field by 3D magnetometers and the atmospheric pressure by an integrated barometer. This 17 sensors are placed with straps and a suit at all relevant body parts: head, pelvis, sternum, upper and lower legs, feet, upper and fore arms, hands and shoulders. Every sensor transmits the measured values wireless with a frame rate of 60 Hz to the Xsens Awinda base station. Based on this data and the Xsens biomechanical model it is possible to extract the center of mass and joint angles between extremities [23]. For the description of human motion in the field of biomechanics, joint angles between adjacent segments in clinical notations are defined and mapped into a common coordinate system. MVN Studio is a software application which controls the used motion capture system. The integrated biomechanical model is based on 22 joint angles which are listed and marked on a virtual skeleton in Tab. I. The joints between the adjacent vertebrae jL5S1 (1), jL4L3 (2), jL1T12 (3) and jT9T8 (4) are not measured directly, they are interpolated in MVN Studio using a model of the spine. Details on the Xsens biomechanical can be seen in [24].

b) Simulation Software: The virtual environment is designed using the simulation software IPG CarMaker. This software is mainly developed for virtual test driving with detailed vehicle dynamic models, which correspond to the behavior of real vehicles including intelligent drivers and highly flexible and manipulatable road components.

Tab. I: Definition of the Xsens MVN biomechanical model

Segment	Joint	Virtual Skeleton
1	jL5S1	
2	jL4L3	
3	jL1T12	
4	jT9T8	
5	jT1C7	
6	jC1Head	
7	jRightC7Shoulder	
8	jRightShoulder	
9	jRightElbow	
10	jRightWrist	
11	jLeftC7Shoulder	
12	jLeftShoulder	
13	jLeftElbow	
14	jLeftWrist	
15	jRightHip	
16	jRightKnee	
17	jRightAnkle	
18	jRightBallFoot	
19	jLeftHip	
20	jLeftKnee	
21	jLeftAnkle	
22	jLeftBallFoot	

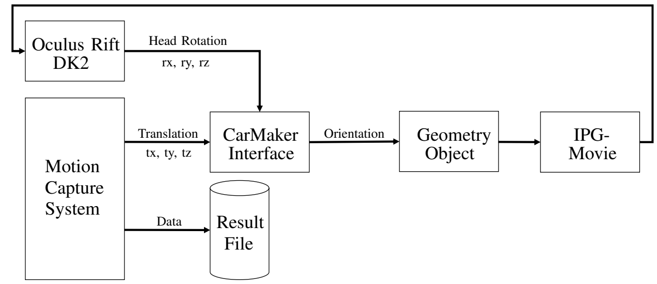


Fig. 2: Design concept of the pedestrian simulator

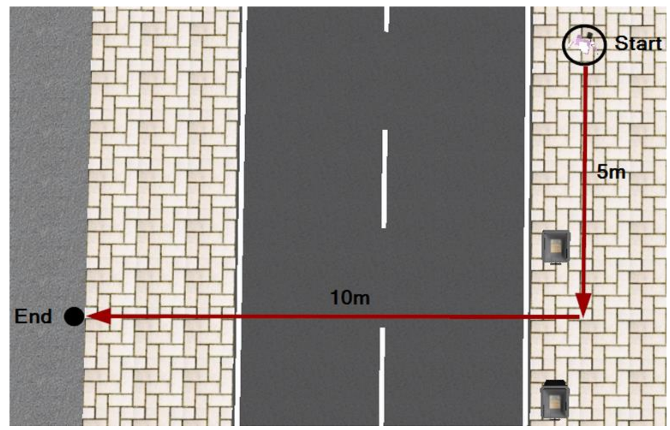


Fig. 3: Scenario procedure of the experimental setup in virtual reality

c) VR - Glasses: For the visual feedback to the test subject, the Oculus Rift DK2 is used. The Oculus Rift produces a stereoscopic image with two screens with a resolution of 960 x 1080 pixel per screen, a 100 degree field of view and an image refresh rate of 75 Hz. The Oculus Rift is equipped with an additional 3D inertial sensor for motion detection.

2) System Setup: Fig. 1 shows the simulator setup, which consits of VR-glasses (1), 17 small and lightweight intertial motion capture sensors (2), a motion data receiver (3) and a notebook with simulation software (4).

In order to enable free motion in the room, the motion data receiver and the notebook are placed on the test subject in a backpack. With this developed pedestrian simulator it is possible to investigate the reaction and behavior of pedestrians in different traffic scenarios in a safe and defined simulation environment.

3) System Configuration: The design concept of the pedestrian simulator is illustrated in Fig. 2. In order to achieve a realistic visual feedback, the position of the test subject and the orientation of the head have to be transferred to the simulation software. The motion capture system transmits the current position of the test subject with 60 Hz to the CarMaker interface. Additionally all motion capture data

Fig. 4: Mixed reality third person view: Participant is located between two virtual trashcans in the middle of the experimental area and aiming to cross the virtual street

is stored in a result file. The CarMaker interface is an user accessible module which enables direct access to variables in the software code for manipulating and adding own application specific functionality to the CarMaker simulation program. The roll, pitch and yaw angle of the test subjects head are transmitted directly from the Oculus Rift to the CarMaker interface.

B. Participants

23 participants with an age range between 18 and 30 years participated in the study. All participants met the requirement of normal or corrected to normal vision by contact lenses for an unrestricted vision using the head-mounted VR-glasses. In order to achieve the best motion capture results, the motion capture sensors must be attached close to the body. Therefore, all subjects were asked to wear closely fitting clothes underneath the motion capture system and sport shoes.

C. Experimental Setup

1) Virtual Environment: The virtual environment in CarMaker was designed as a part of a small city. It was aimed to present the virtual city as realistic as possible to the test subjects. To accomplish this goal, the environment was designed with different buildings like houses, state and office buildings, trees, traffic signs and a petrol station as shown in Fig. 1. For the urban traffic scenario a two lane street was implemented with a width of 6 m. The street segment where the test scenarios took place was a straight road with a length of 100 m. On each side of the road were sidewalks with a width of 3 m. In order to ensure consistent test conditions, vehicles with defined velocities and gaps between the vehicles were added to the simulation. Various objects were added for orientation purposes. Two trashcans on the one side of the road are marking a defined crossing point. On the opposite side of the road a human model was placed, which was marking a defined destination point. The detailed test procedure is described later in section IV.

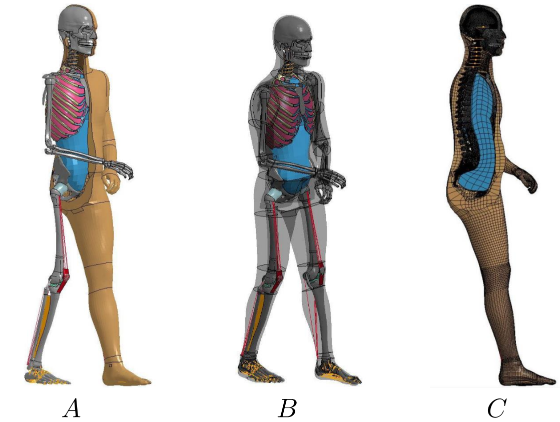


Fig. 5: Summary of GHBMC-PS geometry and basic mesh. (A) Flesh and thoraco-abdominal geometry. (B) Skeletal structure geometry. (C) Lateral view of superficial soft tissue and thoraco-abdominal mesh. [26]

2) FEM-Simulation: Two comparative simulations were run at the Department for Biomechanics and Accident Analysis of the University of Munich (LMU). The objective of these simulations was to investigate and quantify the influence of the pedestrian posture on impact kinematics. A pedestrian impact against a vehicle was therefore simulated using a generic FE front-end model and the simplified HBM pedestrian version of the Global Human Body Model Consortium-owned GHBMC Model, exclusively distributed by Elemance and hereinafter referred to as GHBMC-PS. In a baseline simulation, the HBM was used in the position provided by the model's developer representing the current standard SAE pedestrian posture described in [16]. In a second comparative simulation, the model was positioned according to a selected representative body posture from the experimental part of this study. The geometry of the GHBMC-PS is based on medical imaging and anthropometry of a 50th percentile living male volunteer (height H = 174.9 cm, weight W = 78.6 kg). The geometry was thereby segmented and meshed to obtain a FE model comprising 836053 elements and 538838 nodes. The skeleton is mostly represented by rigid elements within the GHBMC-PS, whereas human soft tissues, such as skin, superficial soft tissues, ligaments as well as cavities mimicking the internal organs are modelled using deformable mainly hexahedral elements. Fig. 5 shows the simplified pedestrian model. [25] [26]

The baseline simulation utilized the GHBMC-PS in the position delivered by the model's developers representing the current standard pedestrian posture described in SAE J2782 [16] targeting a nominal mid-gait stance with the right foot back and the left foot forward. The arms are positioned with hands crossed in front of abdomen and in contact at wrist. For the comparative position, the model was positioned using the data of a more realistic pedestrian body posture obtained within this study. Fig. 6 shows the selected position. The selection criterion for the realistic body posture was subject to having a comparable anthropometry to the GHBMC-PS. The selected representative subject matched the criterion well

Tab. II: Traffic Scenarios

Scenario	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Vehicles approaching from near/far side	left/-	left/-	left/-	-/right	-/right	left/right	left/right	right/right	right/right
Vehicle velocity [km/h]	50/-	65/-	75/-	-/65	-/75	50/70	60/80	50/70	60/80
Gap between vehicles [m]	20	20	25	20	25	30	15	30	15

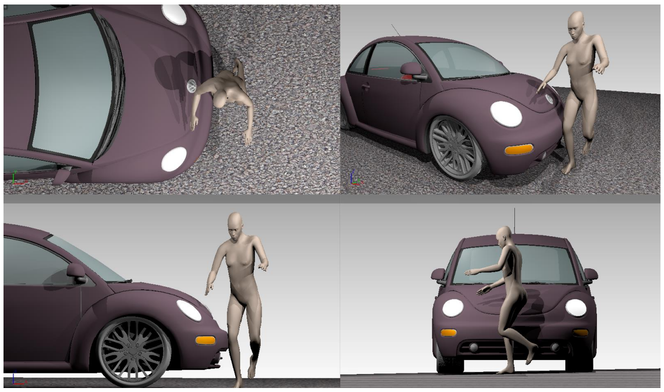


Fig. 6: Selected representative pedestrian posture for positioning the GHBMC-PS within the simulation part of this study in superior (above left), ISO (above right), front view (bottom left) and lateral (bottom right)

with a body height of 176.8 cm. To position the GHBMC-PS, the following measures were targeted to be comparable between volunteer from the experimental part of the study and FE HBM: body height, hip height, angles of shoulder, elbow, hip and knee in x- and z-direction. Fig. 7 shows the two simulated positions in comparison to each other in different views. An initial velocity of 40 km/h was applied to the generic vehicle front as it represents a velocity the buck was validated for and used within consumer testing protocols (e.g. EuroNCAP). The GHBMC-PS was oriented relative to the buck so that it was struck laterally (see Fig. 7). The HBM's vertical position was adjusted to align the struck-side knee at a prescribed height (505 mm over ground level). Gravity was applied to the system for the whole simulation time. The simulation time was set to simulate the entire car-pedestrian impact from the first initial contact of the bumper with the HBM until head-to-windshield contact. To compare both simulations to each other, the following output was derived. Head impact time (t_{HIT}) was defined as the time between the initial contact of the GHBMC-PS and the generic vehicle front ($t_{initial}$) and the contact of the head with the windshield (t_{HCT}). The onset of the corresponding rise of the contact force between vehicle front and GHBMC-PS was determined as time for the initial and the head contact so that t_{HIT} could be calculated by the following formula:

$$t_{HIT} = t_{HCT} - t_{initial} \tag{1}$$

The FEM code LS-DYNA (LSTC, Livermore, CA, USA) was used for running the simulations of this study with the specifications listed in Tab. III.

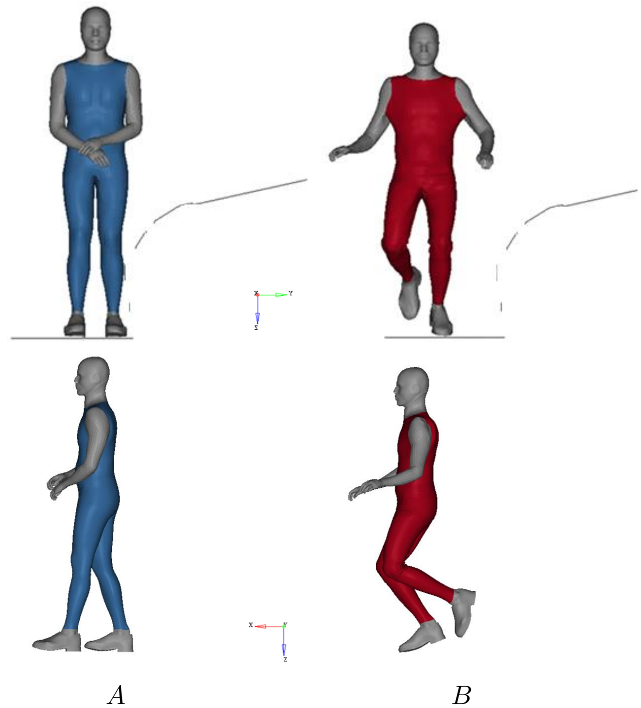


Fig. 7: Two different pedestrian positions in frontal and lateral view used in the simulation part of the study. (A) represents the current standard SAE pedestrian posture (blue), (B) a more realistic pedestrian body posture obtained within this study (red)

IV. Experimental Research

The study was conducted at a closed experimental area, so that it could be carried out in a safe environment without tripping hazard and without the influence of weather conditions.

The study setup was designed in such a way, that no contact with a real obstacle was possible during the test run in the virtual world. The road crossing point and the position of the destination point have been selected so that no collision could occur with the side barrier at any time. Also a sufficient large run-out area was given for running subjects. The floor has a friction coefficient like a typical road, ensuring that no participant slips on the ground.

1) Preparation of Participants: Every subject received an introduction to the pedestrian simulator, an explanation of awareness for symptoms of virtual reality sickness and the information that the subject can stop the virtual study by removing the VR-glasses at any time.

2) Test Procedure: At the beginning, the test subjects were located at the sidewalk, as can be seen in Fig. 3. In order

Tab. III: LS-DYNA build used for the simulations of this study

Version	Precision	Revision	SVN Version	Cluster Platform	OS Level
MPP S R10.0.0	Single	118243	118302	Linux CentOS 6.5 uom	Platform-MPI 8.1.1 Xeon64

Fig. 8: Pose as a result of calculated average values of each joint angle at time of collision taking into account only collisions with vehicles coming from the right

to get a first overview of the scenario and to get used to the virtual reality, the test subjects were asked to move 5 m along the sidewalk. When the participants had reached a defined point, which was marked between two virtual trashcans on the sidewalk, the participant was asked to make himself familiar with the approaching vehicles in the virtual traffic situation, as can be seen in Fig. 4. After the participants made themselves familiar with the virtual traffic situation, they were asked to cross the virtual street if they want to. The participants were free to cross the street in any way (e.g. start pose, velocity, tactic) and also to remove the VR-glasses and abort the test at any time. In case of a virtual car to pedestrian collision the participants impact position on the virtual vehicle was stored. Additionally a marker was set at the current full body motion capture frame for later evaluations of the body pose at time of collision. After completing a scenario the subjects were examined for signs of motion sickness and could continue with the next virtual test scenario if they wanted. Based on this procedure, the study was conducted for the scenarios defined in Tab. II.

V. Results

1) Experimental Results: Based on a total number of 207 crossings (23 subjects performing each nine crossing scenarios) 124 collisions were detected. As a result of the experimental study, the body poses at time of collision were evaluated. In order to obtain the average body and segment orientations at time of collision, the average of each joint angle was calculated which are listed in Tab. I. Since the orientation of the body to the vehicle at time of collision depends on the laterally impact side, only collision poses with vehicles approaching from the right were evaluated in the first step. The resulting pose from the mean values shows that the participants had the arms directed away from the body in an angled posture. The bent legs and the lifted feet indicate that the subjects were in a walking phase in these scenarios. The resulting average body posture can be seen in Fig. 8. In [14] and [13] simulations with different gait stances showed how significant the influence of the gait is on the simulation result in terms of head impact location and time. In [27] it was mentioned that new gait stances are required which reflect a realistic pose of a pedestrian at time of collision. Therefore, a gait analysis was performed on all 124 captured collision poses. It was defined that a foot was lifted off the ground when the motion capture system registered that the foot sensor was 5 cm higher than during the initial calibration. The result shows that in 53% of the collisions the participants had lifted both feet off the ground, which indicates a running phase at time of collision. In 42% of the collisions the participants had one of their feet on the ground and one of their feet lifted off the ground. Only in 5% of the collisions, the participants had both feet on the ground.

2) FEM Simulation Results: Fig. 9 and 10 show the global kinematics of the GHBMC-PS in the standard pedestrian position according to SAE J2782 (left side, blue colored HBM) and in the adapted posture (right side, red colored HBM), which was selected based on a representative body posture from the experimental part of this study, at five different points in time. The time t = 148 ms and t = 158 ms were chosen as they correspond to the head contact times in the two simulations, respectively. In Fig. 9 the frontal view is shown with the vehicle front model blanked, in Fig. 10 the superior view. The GHBMC-PS in the standard position rolls off the lower extremities, the pelvis, upper body, shoulder and head over the vehicle front until the head contacts the windshield at time t = 148 ms. The left arm is thereby trapped between body and hood and the face is slightly looking towards the windshield. The GHBMC-PS in the adapted position similarly rolls off the vehicle front. However, the left arm is located in front and superior of the body resulting in a considerably later head contact time of t = 158 ms. At this point of time the face is looking upwards indicating that the body rolls off more backwards over the back of the body for the adapted posture whereas the GHBMC-PS in the standard position is more forward faced rolling off the frontal part of the body. Head impact times exhibit a measurable influence of the body posture on the kinematics of the pedestrian with the head impact time being 11 ms later for the adapted posture.

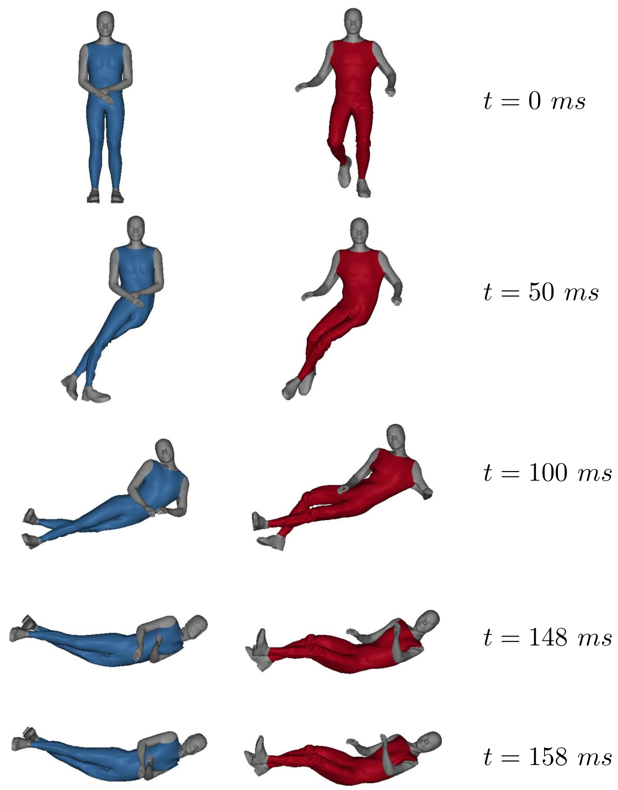


Fig. 9: Global kinematics of the GHBMC-PS in the standard pedestrian position according to SAE J2782 (left side, blue colored HBM) and in the adapted posture (right side, red colored HBM) at five different points in time in frontal view

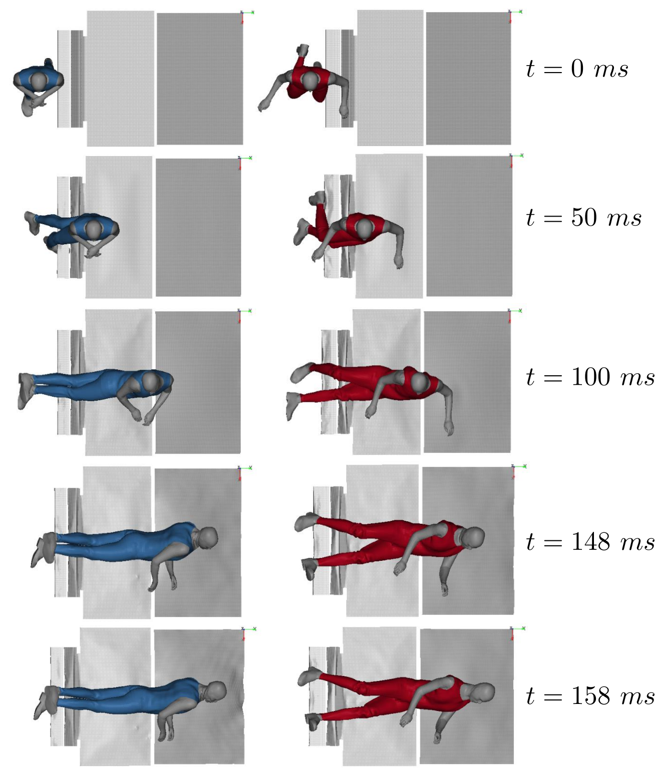


Fig. 10: Global kinematics of the GHBMC-PS in the standard pedestrian position according to SAE J2782 (left side, blue colored HBM) and in the adapted posture (right side, red colored HBM) at five different points in time in superior view

Tab. IV: Head impact time t_{HIT} for the two simulations as well as the peak values of the head CoG linear and rotational acceleration as well as the displacement in z-direction

	Head Impact Time (t_{HIT})
SAE position	147 ms
Adapted position	158 ms

VI. DISCUSSION

Simulating a car-pedestrian impact with a numerical model of a generic vehicle and a FE human body model (HBM) has the potential to optimize active and passive safety systems [28]. However, it has been reported that the posture of a pedestrian at the time of collision with the vehicle has considerable influence on the kinematics of the pedestrian. Within the simulation part of this study, this influence should be investigated and quantified by simulating a car-pedestrian impact with the FEM. Two comparative simulations were therefore run utilizing a generic vehicle front model and the GHBMC-PS FE HBM in two different postures, the standard SAE pedestrian posture described in [16] and in an adapted representative body posture obtained in the experimental part of the study. Major differences between the two body postures were the stance of the models on the ground, the height of the pelvis and therefore the bending of the lower extremities, the position of the upper extremities and the height of the head CoG. Whereas for the SAE position both feet are fully in contact with the ground, the adapted position exhibit a more moving posture with only one foot touching partially the ground. The pelvis is located slightly lower for the adapted posture as the lower extremities are more bend. The arms are not in contact at the wrists in front of the abdomen for the adapted position as in the SAE posture but located lateral to the body. The height of the head CoG is slightly lower for the adapted position due to the bend legs and a more forward crouched torso. These differences in postures resulted in different global kinematics during the car impact and therefore also in different head impact times. Head impact time was chosen to be the primary measure for evaluating the influence of the pedestrian posture on impact kinematics at it is the sole criterion currently used in pedestrian consumer testing protocols. The differences in posture cause the body of the pedestrian roll of the generic vehicle front in different ways. Whereas for the SAE case the body rolls off more the frontal part of the body with the arm consequently located between body and vehicle, the body in the adapted case rolls off more on the back of the body with one arm supporting the body against the vehicle. Especially the role of the upper extremities results in a considerable later head impact time for the adapted case.

In summary, this paper introduces a virtual reality based approach for researching pedestrian to vehicle interaction in critical traffic situations, based on a virtual traffic environment, VR-glasses and a motion capture system, which enable test subjects to enter a defined traffic scenario as a pedestrian. If a virtual collision occurred, the collision was detected and the current body posture of the test subject was captured using the motion capture system. Selected collisions were further analyzed by FEM simulation, using the captured body posture and vehicle speed as input values.

The study indicated that the pedestrian posture at the time of collision with a vehicle has a measurable influence on the kinematics of the pedestrian and on measures which are currently used within consumer testing protocols to evaluate traffic safety for pedestrians. It is therefore essential, to not only optimize passive and active safety systems with solely one standard posture, but with a variety of body postures representing real world impact scenarios.

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