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The predictive capacity of the MADYMO ellipsoid pedestrian model for pedestrian ground contact kinematics and injury evaluation

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31 **1. Introduction**

32 The World Health Organization (WHO) estimates that more than 300,000 pedestrians have died in
33 2019 (WHO 2020), based on its Global Status Report on Road Safety 2018 (WHO 2018). Pedestrian
34 collisions usually involve a primary contact with the vehicle, followed by a secondary contact with
35 the ground (Han *et al.* 2018, Shang 2020). Accordingly, although most research has focused on
36 vehicle contact (Kerrigan *et al.* 2007, Yao *et al.* 2008), the significance of the ground contact has also
37 been emphasized (Simms and Wood 2006, Crocetta *et al.* 2015, Han *et al.* 2018, Shang *et al.* 2018,
38 Shi *et al.* 2019, Shang *et al.* 2020b). A recent analysis based on German real-world crash data
39 (GIDAS) showed that 43% of 1221 selected cases had injuries subjected to ground contact,
40 demonstrating the importance of ground related pedestrian injuries and providing significant
41 motivation for countermeasures to prevent or moderate pedestrian injuries from ground contact
42 (Shang *et al.* 2018). (Shang *et al.* 2020b) recently conducted six cadaver tests which recorded the
43 whole process from vehicle contact until after the end of the ground contact. They observed that peak
44 linear accelerations in ground contact are generally higher than for the vehicle contact. They also
45 observed a high predicted risk of rotationally induced brain injury from ground contact, even for very
46 low vehicle collision speeds.

47 However, many open questions remain regarding the influence of vehicle front shape and the design
48 of potential countermeasures to minimize pedestrian ground contact injuries, and a suitably validated
49 computational model is a much more sustainable tool for addressing these than cadaver experiments.

50 The MADYMO 50th percentile male pedestrian model, developed by TNO Automotive, is the
51 most commonly used multibody pedestrian models for vulnerable road user crash reconstruction (van
52 Hoof *et al.* 2003, van Rooij *et al.* 2003, Simms and Wood 2006, Untaroiu *et al.* 2009, Elliott *et al.*
53 2012, Xu *et al.* 2016, Shang *et al.* 2018). The model was validated for both full model (Ishikawa *et al.*
54 1993) and model segments such as tibia and femur static 3-point bending tests, cadaver side
55 impact tests for the pelvis, thorax and shoulder, cadaver leg impactor tests for bending moment and
56 shear force of lower extremities (Kajzer *et al.* 1993). De Lange *et al.* (DeLange *et al.* 2006) verified
57 the kinematics of the MADYMO pedestrian model with eighteen full vehicle-pedestrian impact tests.
58 However, the validation was only for vehicle contact and not for ground contact, even though it has
59 since been applied for analyzing the ground contact (Crocetta *et al.* 2015, Zou *et al.* 2019). (Crocetta
60 *et al.* 2015) defined six different pedestrian ground impact mechanisms by simulating hundreds of

61 impact configurations with different vehicle shapes, pedestrian heights and vehicle speeds, with
62 partial validation by comparison to real-world videos (Barry and Simms 2016). The model has also
63 been applied in the use of potential braking related countermeasures (Zou *et al.* 2019). However, the
64 capacity of the MADYMO pedestrian model to replicate kinematics of individual pedestrian ground
65 contact collisions remains unknown.

66

67 Researchers also developed other multibody or finite element pedestrian models for vehicle-
68 pedestrian collisions. (Yang and Lovsund 1997) developed a 3D MB pedestrian model with emphasis
69 on the head and lower extremities. The model consists of fifteen body segments with fourteen joints.
70 The leg segments are breakable (Yang *et al.* 1993) and the knee joint formulation (Yang *et al.* 1995)
71 facilitates biofidelic responses of the knees and leg fracture. The model was validated based on
72 pedestrian substitutes' kinematics, the body segments' accelerations, contact forces, and failure
73 descriptions compared with previously published cadaver impacts (Ishikawa *et al.* 1993). Finite
74 element pedestrian models such as THUMS (Maeno and Hasegawa 2001, Iwamoto *et al.* 2003) and
75 GHBMC (Untaroiu *et al.* 2016) pedestrian models are developed to simulate deformable vehicle-
76 pedestrian impact scenarios. However, none of these models have been validated for ground contact.

77

78 In summary, a variety of pedestrian models (multibody and finite element) have been developed and
79 applied to vulnerable road user crashes. These have been validated based on lower extremity bending
80 and shear loadings, the head response including acceleration and force, head trajectories, whole-body
81 kinematics etc. However, all models are validated for the vehicle impact only, and model validations
82 for ground contact are so far lacking. The importance of pedestrian ground contact is growing and
83 the risk of suffering serious head brain injury due to ground contact has been recently highlighted
84 (Shang *et al.* 2018, Shang *et al.* 2020b). Given the high cost of cadaver tests, there is significant
85 value in a pedestrian model which can simulate the ground impact and can be applied in large-
86 sample parametric study such as virtual test system (Li *et al.* 2018). The recent staged cadaver
87 impact tests (Shang *et al.* 2020b) provide a valuable experimental reference set, including pedestrian
88 kinematics and injury criteria evaluations (skull fracture, *HIC* and *BrIC*) for multi-body model
89 assessment.

90 Accordingly, the aims of the current study are to:

- 91 1) reconstruct the cadaver impact tests of (Shang *et al.* 2020b) to assess the capability of the
92 MADYMO pedestrian model for use in ground contact scenarios, and assess the
93 difference between the MADYMO multibody model and the cadaver in post-impact
94 kinematics and head injury criteria predictions.
- 95 2) Perform sensitivity studies to assess the influence of the vehicle pedestrian contact
96 characteristics, the influence of initial pedestrian position on subsequent pedestrian
97 ground contact and the effect of internal damping on overall body kinematics.

98 If the pedestrian model can reasonably replicate kinematics and injury outcomes, it may be suitable
99 for investigating the effect of vehicle front shape on the risk of pedestrian ground contact injuries
100 over a broad range of collision configurations. Moreover, it could be used for developing active
101 countermeasures to prevent pedestrian ground contact related injuries, such as controlled braking or
102 airbag technologies (Khaykin and Larner 2016, Zou *et al.* 2019).

104 **2. *Materials and methods***

105 The MADYMO ellipsoid multibody pedestrian model, as well as simplified vehicle models, were
106 employed to assess their performance in ground contact, by comparison with the cadaver tests
107 reported in (Shang *et al.* 2020b), see Figure 1.

109 Given uncertainty in several input characteristics of the models, sensitivity studies were designed to
110 assess the influence of the vehicle to pedestrian contact definition (loading and unloading functions,
111 hysteresis), internal damping in the pedestrian models and the initial pedestrian joint angles.

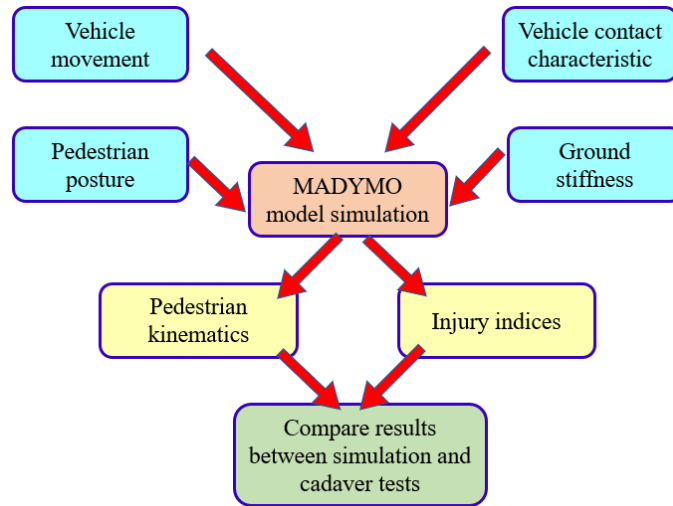


Figure 1: Steps followed in assessing the multibody models

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2.1. Multibody vehicle models

114

115 Simplified multibody vehicle models were built in MADYMO, with the geometry based on (The-
 116 Blueprints) to represent the vehicles tested in (Shang *et al.* 2020b). Each vehicle model consists of a
 117 lower bumper, bumper, bonnet leading edge, bonnet, windshield, wheels and roof, see Figure 2.

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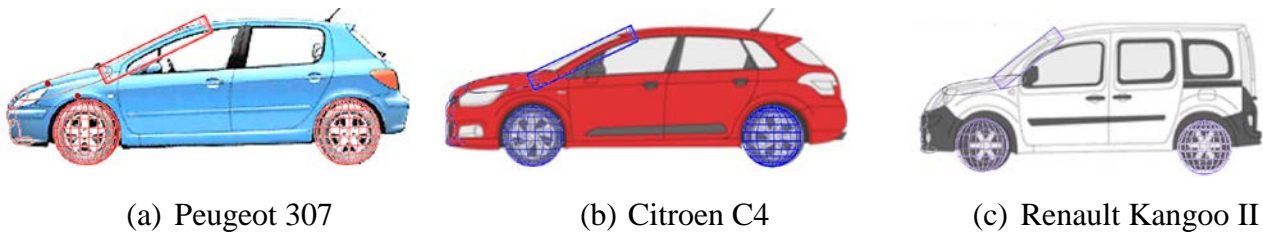


Figure 2 The vehicle models with the simplified MADYMO models

119

2.2. Pedestrian models

120

121 The heights and weights of the pedestrian cadavers varied, as shown in Table 1 of (Shang *et al.*
 122 2020b), replicated here as Appendix A and these were replicated by scaling the MADYMO 50th
 123 percentile pedestrian model using a customized Matlab code based on the pedestrian's height and
 124 weight. This global scaling does not address relative differences in body segment proportions. The
 125 scaled multibody models, as well as the corresponding pedestrian cadavers are shown in Figure 3.
 126 The initial postures (joint angles) of the models were adjusted based on the measurements of cadaver
 127 poses from the side and the front views which were captured pre-impact. Due to the joint limitation
 128 of the pedestrian model and the segment dimension differences, some differences between cadaver

129 and the simulation postures exist, see for example the left forearm in Figure 3 (a). For Test 05 in
130 Figure 3 (e), the posture is the result of difficulties with initial placement of the cadaver which had
131 very low mass (38kg) and unusually stiff joints (the cause of this is unknown as full medical histories
132 were not available).
133

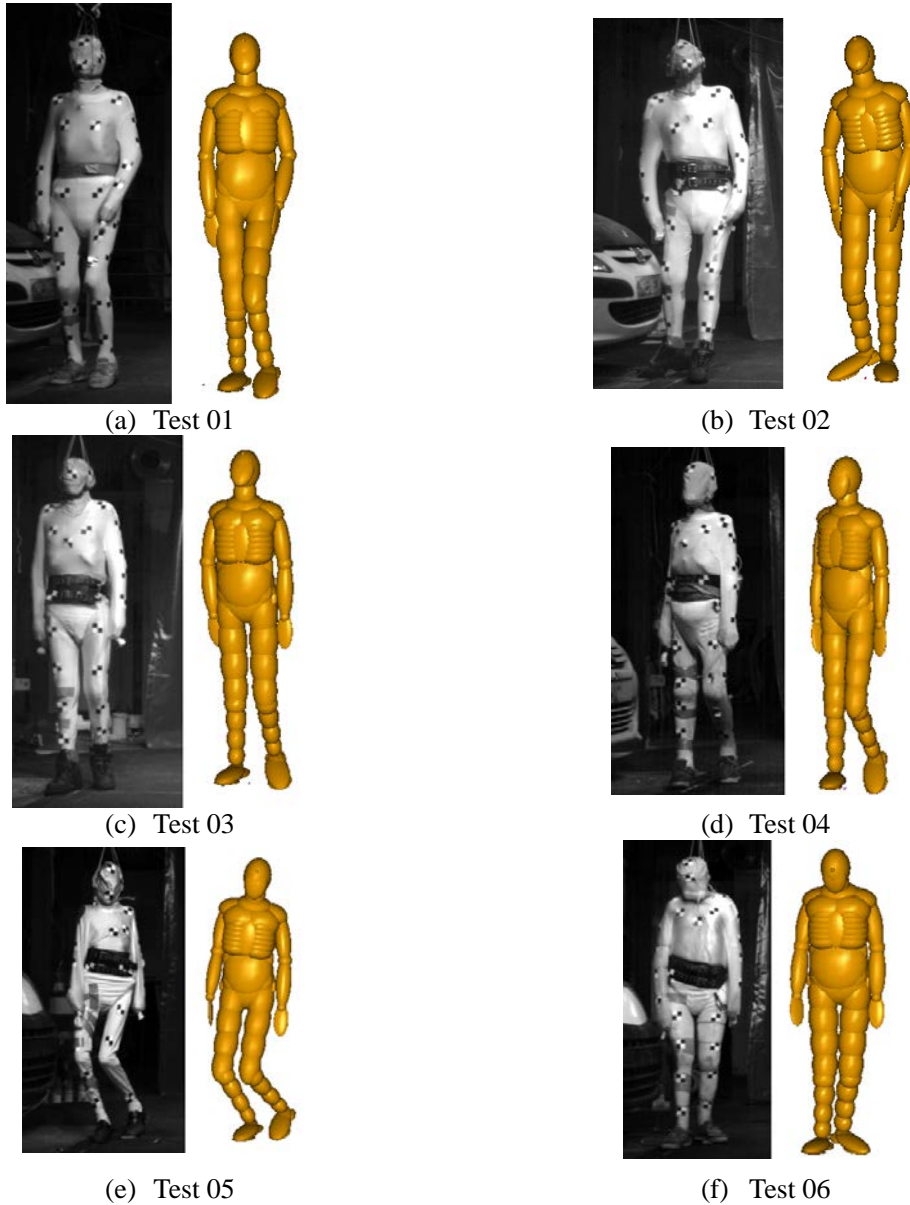


Figure 3 The initial postures of PMHS pedestrians and the corresponding scaled multi-body models

134 2.3. Movement input of the multibody vehicle models

135 The planar time-displacement curves in the X (horizontal) direction and the Z (vertical) direction,
136 and the time-rotation curve of the vehicle, were extracted every 20ms (overall impact duration was
137 approximately one second) using a customized Matlab script and used to prescribe the vehicle

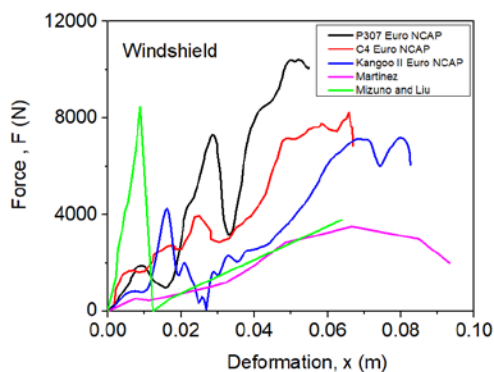
138 motion in the models. The general steps for selecting the tracking points are as shown in Appendix
139 B.

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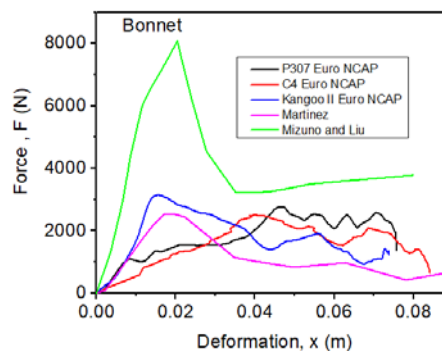
141 2.4. Contact characteristic applied on the MB vehicle model

142 Three sources of vehicle contact characteristic were available: the published force-deformation
143 characteristics derived from impactor tests (Martinez *et al.* 2007), recent test on the actual vehicle
144 types performed by the European New Car Assessment Programme (EURO-NCAP) (Euro-NCAP)
145 and another older force deformation characteristics from impactor tests (Mizuno and Kajzer 2000)
146 and (Liu *et al.* 2002). The windshield and bonnet stiffness from (Mizuno and Kajzer 2000) were
147 obtained by impactor tests and the stiffness of bonnet leading edge and bumper were obtained from
148 leg form tests by (Liu *et al.* 2002). This combination of vehicle contact characteristic has previously
149 been used by (Li *et al.* 2016) for a virtual test system. Euro NCAP assesses the pedestrian safety
150 performance of new cars with a rating (up to 5-star) based on sub-system impactor tests (Hobbs and
151 McDonough 1998, Euro-NCAP 2010). (Martinez *et al.* 2007) summarized 425 Euro NCAP tests and
152 then estimated a series of simplified average stiffness curves. The force-deformation curves of each
153 tested vehicle from the Euro NCAP tests as well as the force-deformation curves from (Martinez *et*
154 *al.* 2007) and (Mizuno and Kajzer 2000) are shown in Figure 4. The detailed process of obtaining the
155 vehicle front stiffness by using subsystem impactors can be found in (Martinez *et al.* 2007).

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(a) windshield



(b) bonnet

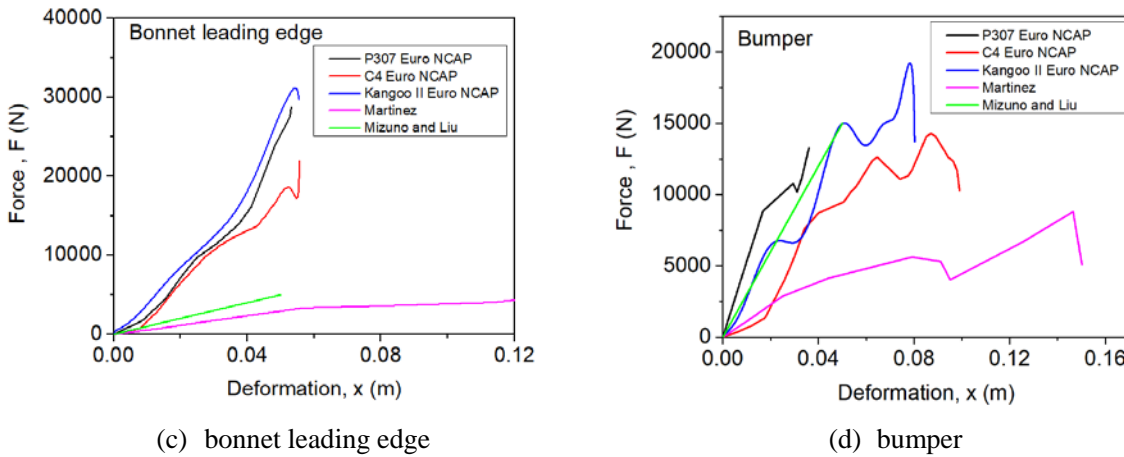


Figure 4 Force-deformation contact characteristics of vehicle front components from different sources

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158 **2.5. Ground contact stiffness**

159 Considering the individual differences of the tested cadavers and also the different locations on the
 160 head (some of the head contacts occurred to the face while others occurred to the posterior of the
 161 head), the ground contact stiffness was set individually in MADYMO for each reconstruction. To
 162 estimate the contact stiffness, a multibody sphere with inertia properties matching the head and
 163 initial linear and angular velocities matching the experimental head kinematics just prior to head
 164 ground contact was used to simulate the head impacts with the ground, see Table 1. The method used
 165 to estimate the contact stiffness of the ground was based on the assumption that a quarter wave of
 166 simple harmonic motion (Triana and Fajardo 2013) reasonably models head acceleration until the
 167 peak is reached in the head ground impact, see Equation 1. From this, stiffness is calculated based on
 168 the peak acceleration and speed change.

169

Table 1 The input parameter of the multibody sphere (simplified head model)

Parameter	Input
Head Mass	4.5kg
Inertia	(2.08e-02 2.37e-02 1.53e-02 0 0 0) kg·m ² (directly from MADYMO 50 th percentile pedestrian model)
Linear speed	From (Shang <i>et al.</i> 2020b)
Angular speed	From (Shang <i>et al.</i> 2020b)
Initial position	0.02m high from the ground in vertical direction

170

171

172

$$\sqrt{\frac{m}{K}} = \omega = \frac{1}{\Delta T} = \frac{1}{\left(\frac{\Delta V}{Acc_{peak}}\right)} = \frac{Acc_{peak}}{\Delta V}$$

$$K = m \times \left(\frac{\Delta V}{Acc_{peak}}\right)^2$$

Equation 1

173

174 where m is the mass of the head, ω is the natural frequency, ΔT is the time duration of the impact,
 175 ΔV is the speed change during impact and Acc_{peak} is the peak acceleration. The stiffness (K)
 176 calculated for each test and the anterior/posterior head contact location are shown in Figure 5. The
 177 head ground contact characteristics for Test 06 is not listed as the acceleration measurement was
 178 corrupted during ground contact. As the input of Test 06 was similar to Test 05 and the pedestrian
 179 ground contact mechanisms of the two tests were same, the stiffness of the ground for Test 06 was
 180 set as same as that of Test 05. The comparison of the accelerations obtained from the simplified head
 181 model with each corresponding cadaver tests are illustrated in Figure 6, and the average values were
 182 applied for posterior and anterior head contacts. The average value of K from Test 01, Test 02 and
 183 Test 05 was used to define K_p (posterior), as shown in Table 2, for the 30 kph tests, which have a
 184 relatively high ground stiffness due to the posterior head impact. In contrast, in Test 03 and Test 04,
 185 the front softer part of the head, such as the nose and face impacted the ground first, namely the
 186 anterior head impact, and the ground contact stiffness in these two tests was set as K_a (anterior) as
 187 shown in Table 2, using the average value of K from the corresponding tests. K_p and K_a were then
 188 chosen as head ground contact characteristic depending on which area of the head impacts the
 189 ground first, as determined in a pre-simulation.

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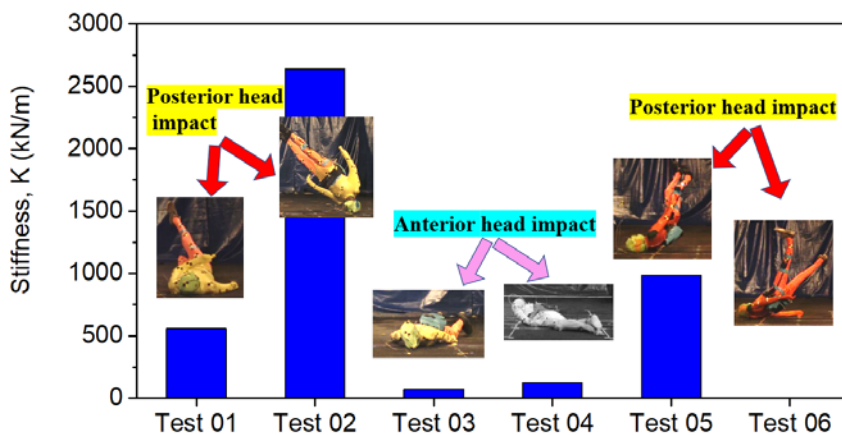
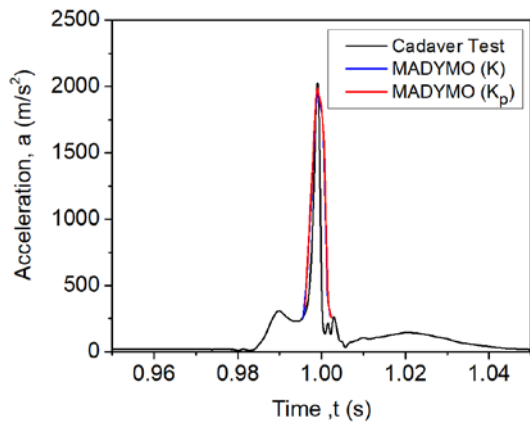
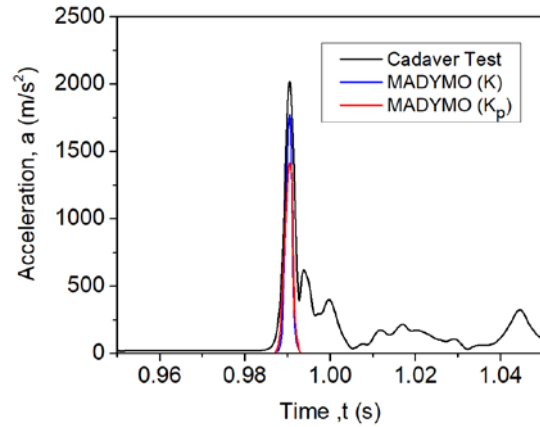


Figure 5 Ground stiffness for each test calculated

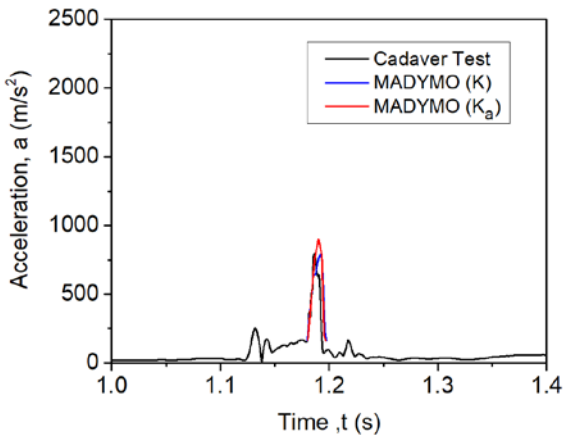
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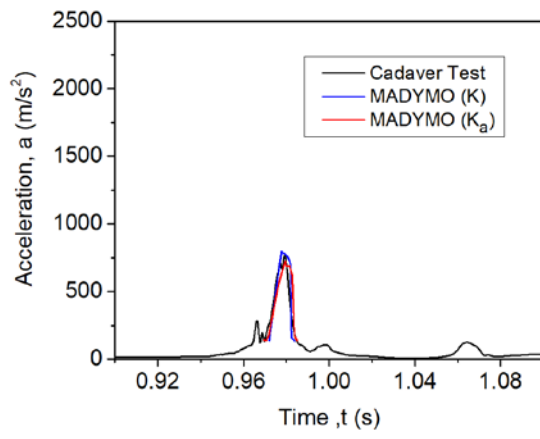
(a) Test 01



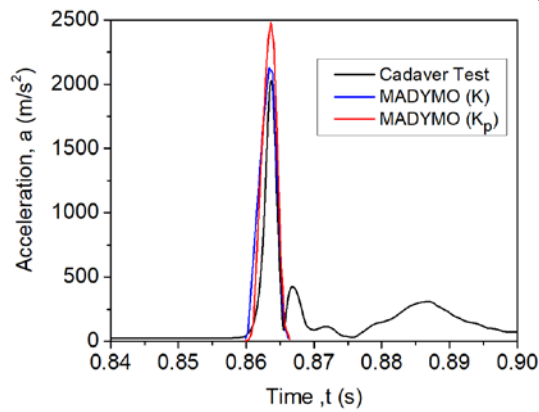
(b) Test 02



(c) Test 03



(d) Test 04



(e) Test 05

Figure 6 Comparison of the accelerations obtained from simplified head model test by using K and K_a or K_p (the comparison of Test 06 was not given because the experimental head acceleration was corrupted)

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Table 2 Stiffness of ground applied in MADYMO simulations

	Value	Test used for reconstruction
k_p	1400 kN/m	Test 01, Test 02, Test 05 and Test 06
k_a	97 kN/m	Test 03 and Test 04

199

200 **2.6 Injury Assessments**

201 Assessments of head injury caused by translational accelerations were approximated using the *HIC*
202 criterion, whereas injuries caused by rotational angular velocities were approximated using the *BrIC*
203 criterion. It is noted this is not the actual *HIC* as it was not possible to fix the accelerometer to head
204 CG in the cadaver tests for practical reasons, while the accelerometers can be fixed in the mouth, it is
205 possible to apply the *HIC* computation to the head accelerometer data with an approximate 10%
206 difference (Shang *et al.* 2020b). Evaluation of *UBrIC* (Gabler *et al.* 2018) instead of *BrIC*
207 (Takhounts *et al.* 2013) would be preferable but was not possible due experimental limitations in the
208 cadaver tests of (Shang *et al.* 2020b).

209 **3. Simulation results**

210 The six staged tests (Shang *et al.* 2020b) were reconstructed and simulated using the MADYMO
211 platform. Each test was simulated using the three different vehicle contact characteristics (Euro-
212 NCAP), (Mizuno and Kajzer 2000, Liu *et al.* 2002) and (Martinez *et al.* 2007), see Figure 4.
213 Pedestrian kinematics and head injury predictions (HIC and BrIC) from vehicle contact and ground
214 contact were compared between the simulation and the corresponding experiment, see Figure 7 and
215 Figure 8.

216 **3.1. Pedestrian kinematics**

217 The key event timings of the vehicle-pedestrian impact from the staged tests and simulations as well
218 as the ground contact mechanisms are compared, see Table 3. The ground contact mechanisms are
219 summarized by assessing the whole-body rotation angles and the posture before landing, with
220 reference to the definition of (Crocetta *et al.* 2015). Overlaying the video still shots from the
221 experiments with the simulations was not practical due to camera projection issues. In Test 01 and
222 Test 02, pedestrian vehicle separation times are generally earlier in the simulations than in the

223 cadaver tests. However, the head ground contacts occurred more than 100ms earlier for the
 224 simulation in Test 01 but late in Test 02.

225 Table 3-1 Comparison of key events (s) of Test 01

Contact characteristic source	$t_{\text{head-vehicle contact}}$ (s)	$t_{\text{separation}}$ (s)	$t_{\text{head-ground contact}}$ (s)	Ground contact mechanism, from (Crocetta <i>et al.</i> 2015)
Staged test	0.145	0.770	0.995	M1
Mizuno and Liu ¹	0.140	0.595	0.845	M3
Martinez	0.140	0.615	0.875	M3
EU NCAP	0.145	0.610	0.865	M3

226
227 Table 3-2 Comparison of key events (s) of Test 02

Contact characteristic source	$t_{\text{head-vehicle contact}}$ (s)	$t_{\text{separation}}$ (s)	$t_{\text{head-ground contact}}$ (s)	Ground contact mechanism, from (Crocetta <i>et al.</i> 2015)
Staged test	0.153	0.710	0.986	M3
Mizuno and Liu	0.150	0.625	1.045	M3
Martinez	0.150	0.615	1.020	M3
EU NCAP	0.150	0.655	1.070	M3

228
229
230 Table 3-3 Comparison of key events (s) of Test 03

Contact characteristic source	$t_{\text{head-vehicle contact}}$ (s)	$t_{\text{separation}}$ (s)	$t_{\text{head-ground contact}}$ (s)	Ground contact mechanism, from (Crocetta <i>et al.</i> 2015)
Staged test	No show	0.834	1.180	M2
Mizuno and Liu	0.170	0.845	1.1170	M2
Martinez	0.170	0.805	1.1095	M2
EU NCAP	0.160	0.800	1.1130	M2

231
232 Table 3-4 Comparison of key events (s) of Test 04

Contact characteristic source	$t_{\text{head-vehicle contact}}$ (s)	$t_{\text{separation}}$ (s)	$t_{\text{head-ground contact}}$ (s)	Ground contact mechanism, from (Crocetta <i>et al.</i> 2015)
Staged test	0.169	0.740	0.970	M2
Mizuno and Liu	0.185	0.745	1.030	M2
Martinez	0.185	0.745	1.255	M2
EU NCAP	0.185	0.705	1.190	M2

233
234 Table 3-5 Comparison of key events (s) of Test 05

Contact characteristic	$t_{\text{head-vehicle contact}}$ (s)	$t_{\text{separation}}$ (s)	$t_{\text{head-ground contact}}$ (s)	Ground contact mechanism, from
------------------------	---------------------------------------	-----------------------------	--------------------------------------	--------------------------------

¹ The contact characteristics used in the simulations are from these authors correspondingly.

source	(Crocetta <i>et al.</i> 2015)			
Staged test	0.098	0.647	0.860	M1
Mizuno and Liu	0.120	0.735	1.790	M1/ M2
Martinez	0.120	0.735	0.990	M1/ M2
EU NCAP	0.115	0.735	1.040	M1/ M2

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Table 3-6 Comparison of key events (s) of Test 06

Contact characteristic source	$t_{\text{head-vehicle contact}}$ (s)	$t_{\text{separation}}$ (s)	$t_{\text{head-ground contact}}$ (s)	Ground contact mechanism, from (Crocetta <i>et al.</i> 2015)
Staged test	0.110	0.727	0.936	M1
Mizuno and Liu	0.135	0.725	0.945	M1/ M2
Martinez	0.135	0.690	0.895	M1/ M2
EU NCAP	0.130	0.680	0.925	M1/ M2

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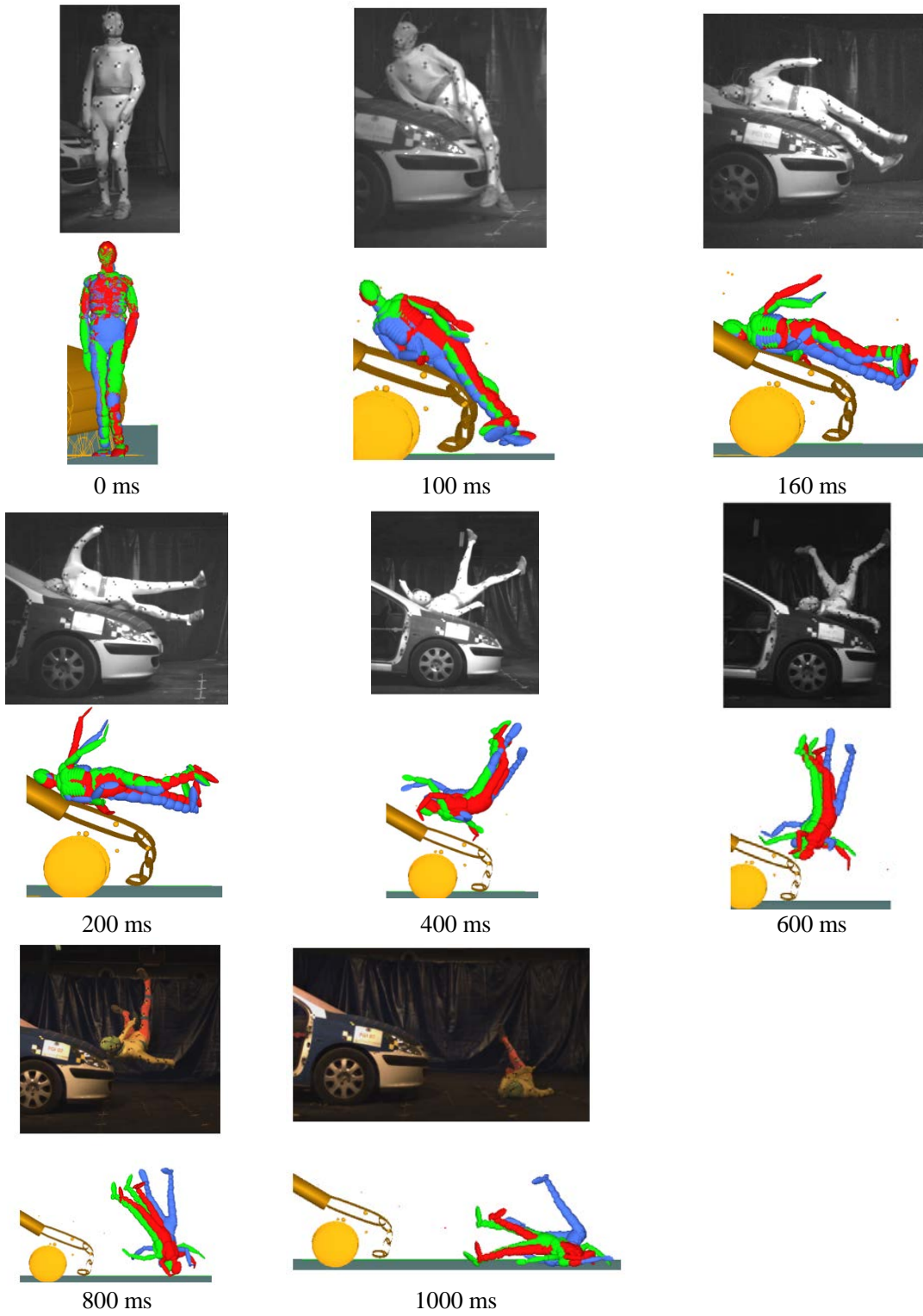


Figure 7-1 Test 01: Sequences of vehicle-pedestrian impact experiment compared with MB simulations. Contact characteristic of vehicle front applied from (Green model: EU NCAP; Blue model: Martinez; Red model: Mizuno)

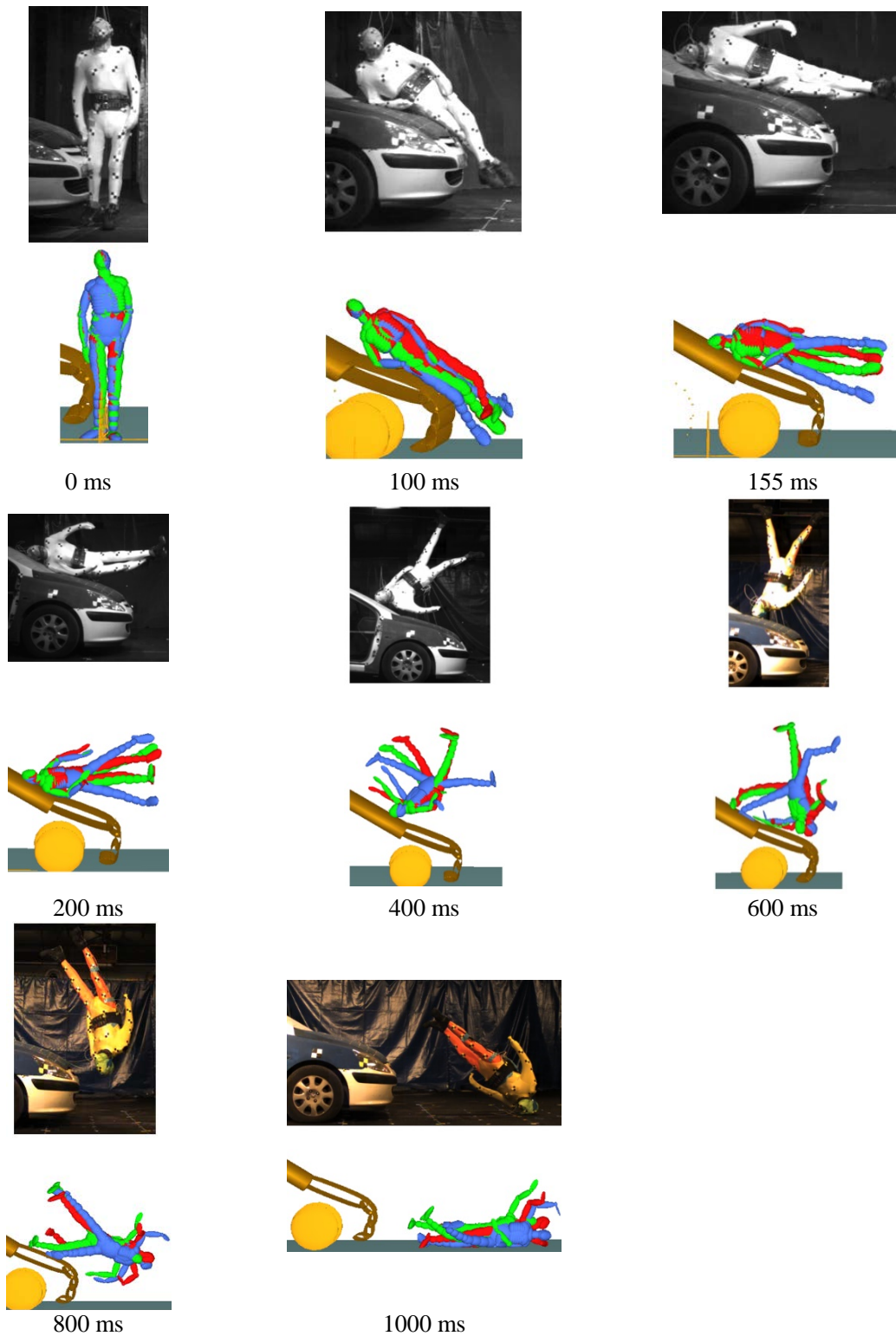


Figure 7-2 Test 02: Sequences of vehicle-pedestrian impact experiment compared with MB simulations. Contact characteristic of vehicle front applied from (Green model: EU NCAP; Blue model: Martinez; Red model: Mizuno)

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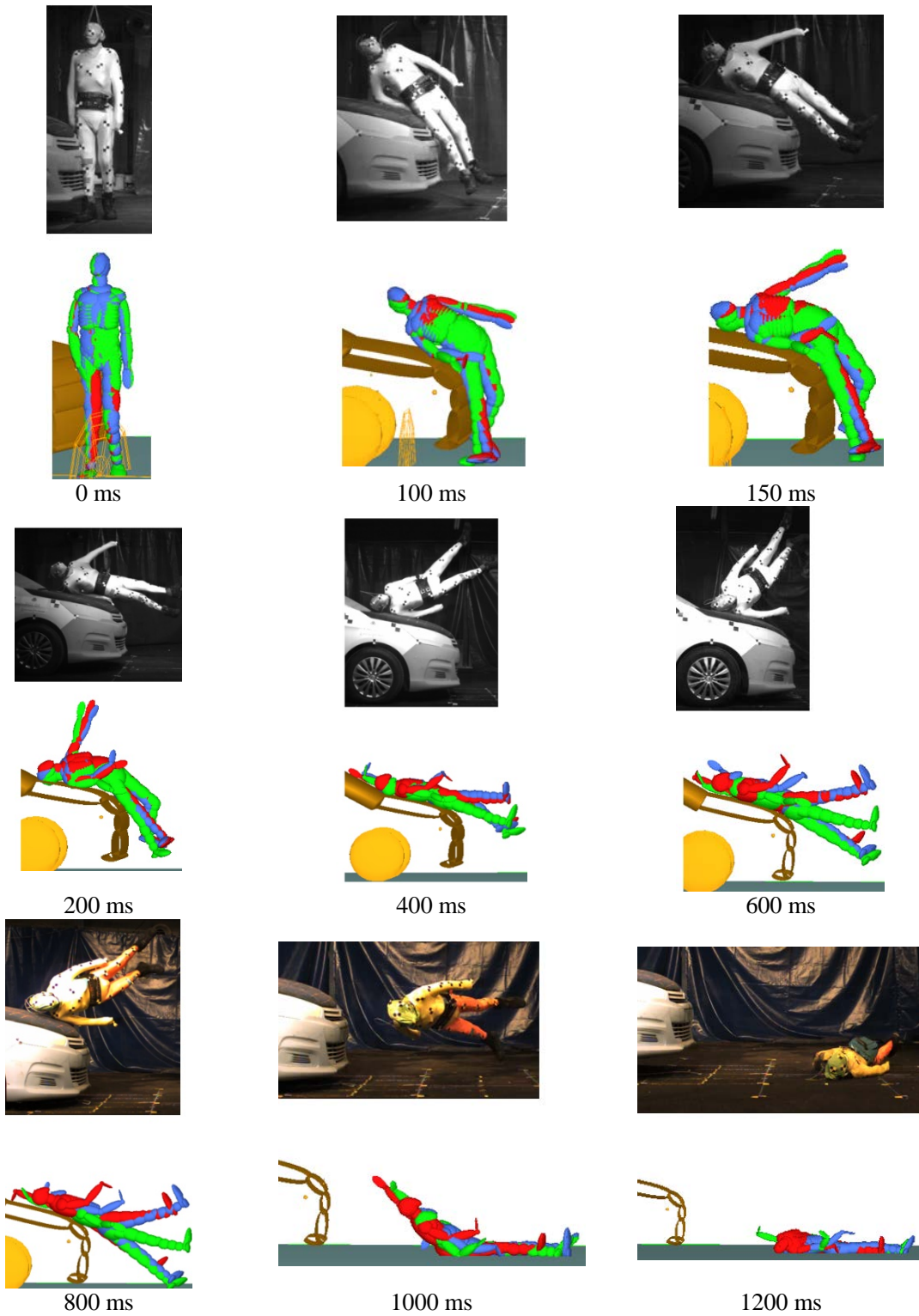


Figure 7-3 Test 03: Sequences of vehicle-pedestrian impact experiment compared with MB simulations. Contact characteristic of vehicle front applied from (Green model: EU NCAP; Blue model: Martinez; Red model: Mizuno)

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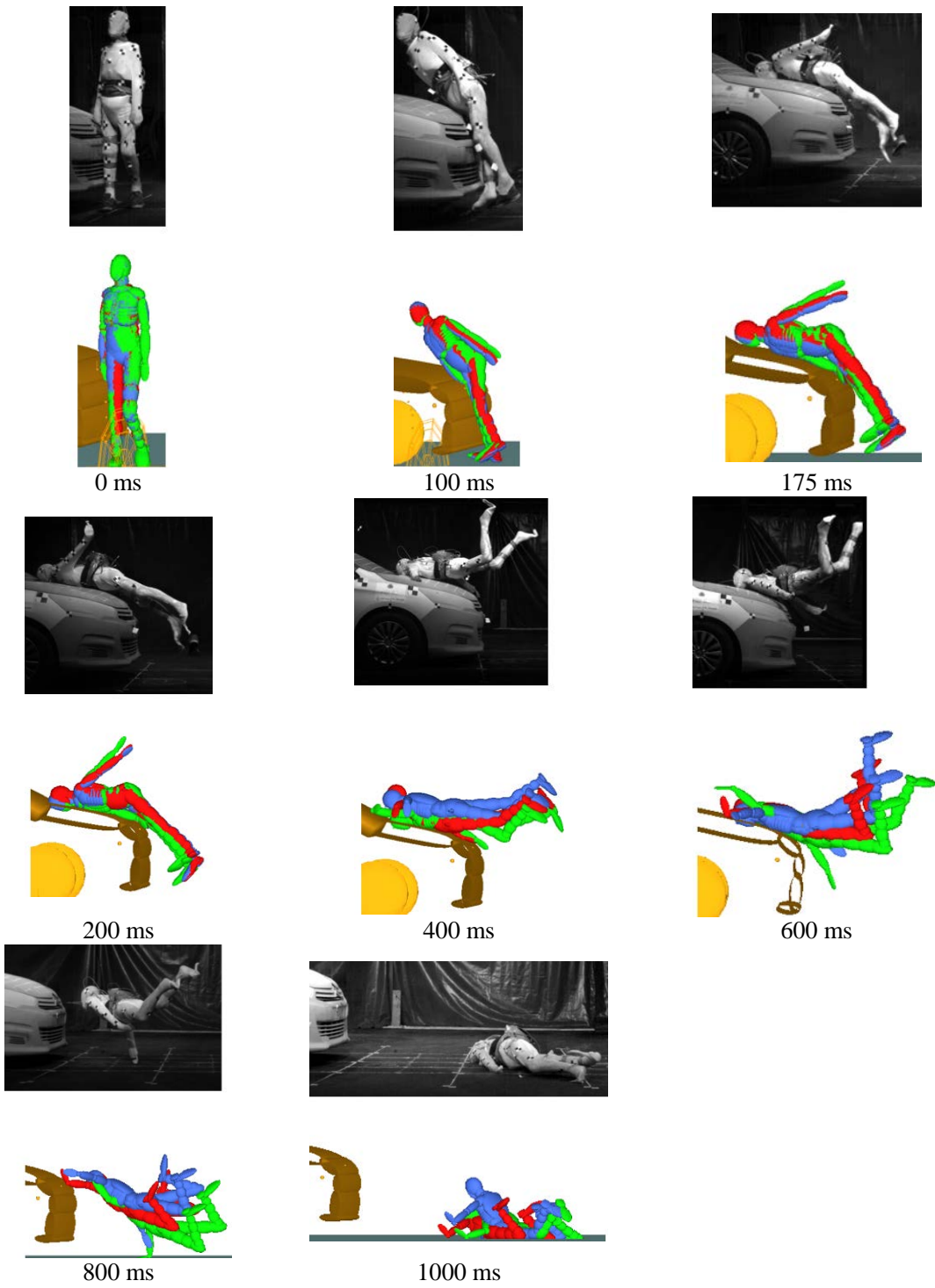


Figure 7-4 Test 04: Sequences of vehicle-pedestrian impact experiment compared with MB simulations. Contact characteristic of vehicle front applied from (Green model: EU NCAP; Blue model: Martinez; Red model: Mizuno)

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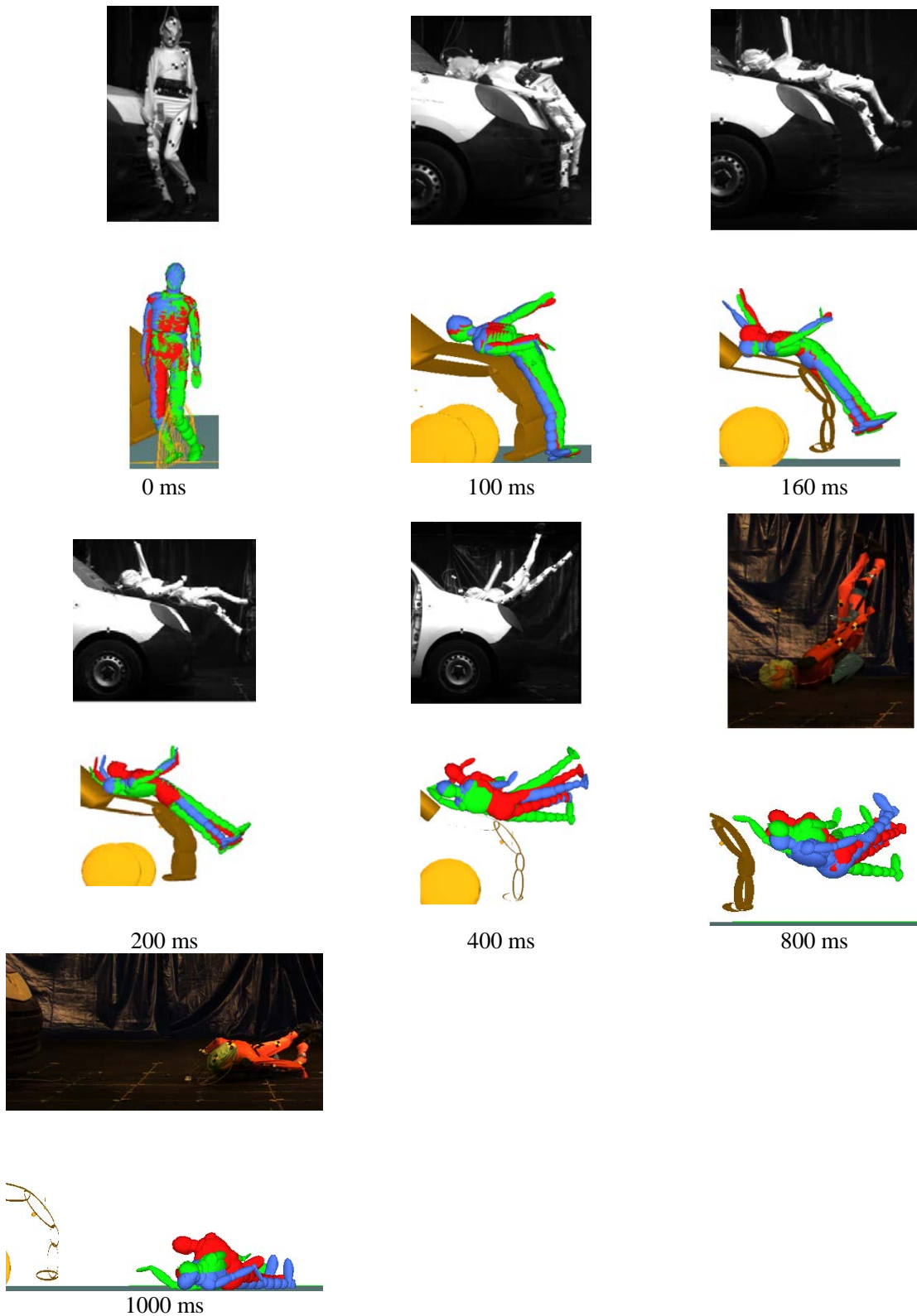


Figure 7-5 Test 05: Sequences of vehicle-pedestrian impact experiment compared with MB simulations. Contact characteristic of vehicle front applied from (Green model: EU NCAP; Blue model: Martinez; Red model: Mizuno)

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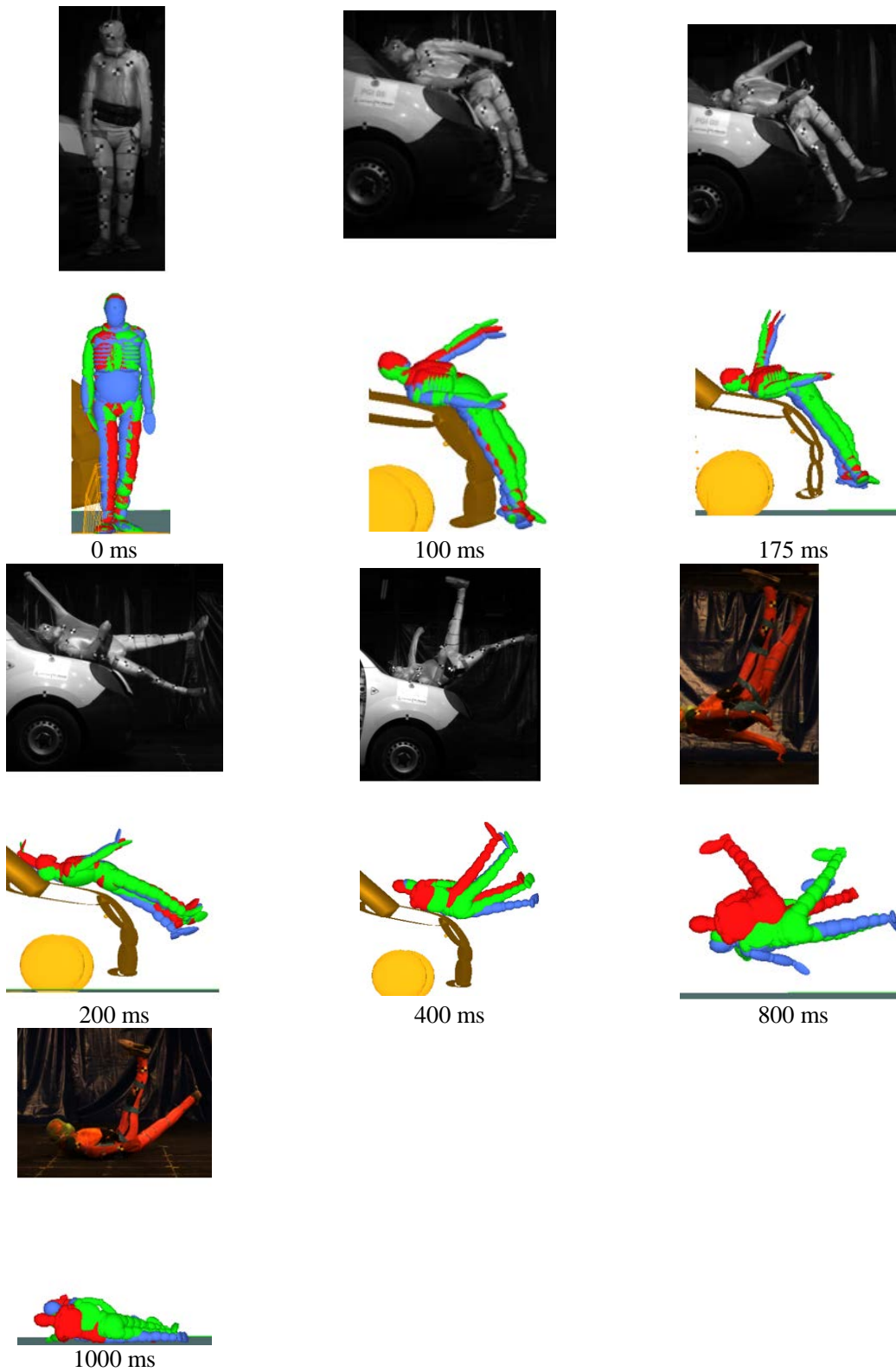


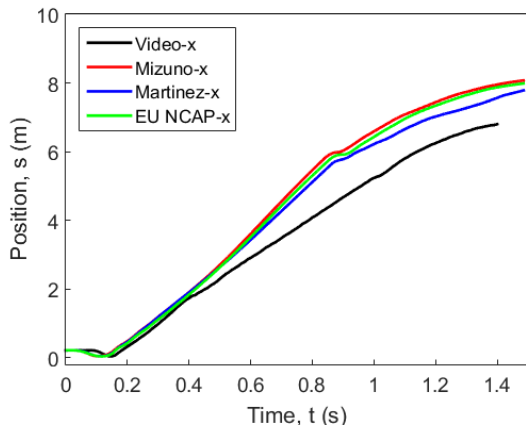
Figure 7-6 Test 06: Sequences of vehicle-pedestrian impact experiment compared with simulations. Contact characteristic of vehicle front applied from (Green model: EU NCAP; Blue model: Martinez; Red model: Mizuno)

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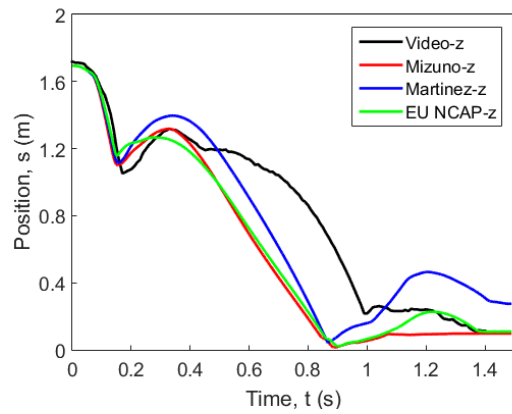
253 **3.2. Pedestrian planar head trajectories**

254 Pedestrian planar head trajectories (tracked based on the marker on pedestrian forehead) in both the
 255 X (horizontal, positive direction of vehicle travel) and Z (vertically upwards) directions from staged
 256 tests and the simulations are compared, see Figure 8. Appendix Figure B1 shows the definition of the
 257 coordinate system after (Shang *et al.* 2020b). For Test 01 and Test 02, the horizontal head motion in
 258 the simulations is greater than was observed in the experiments.

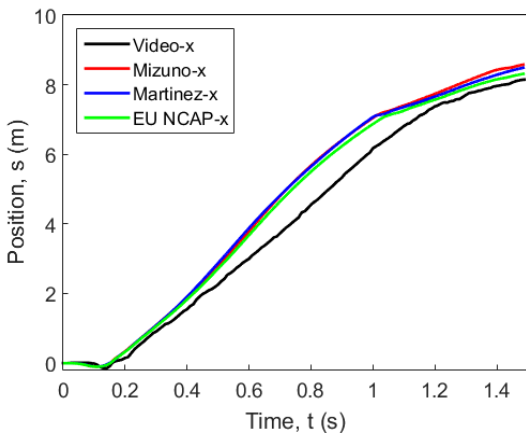
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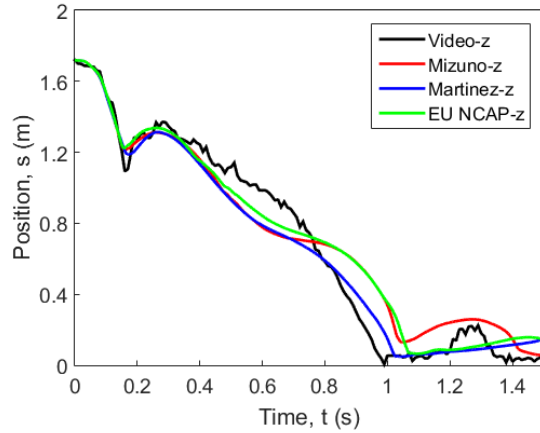
(a) Head marker-x T1



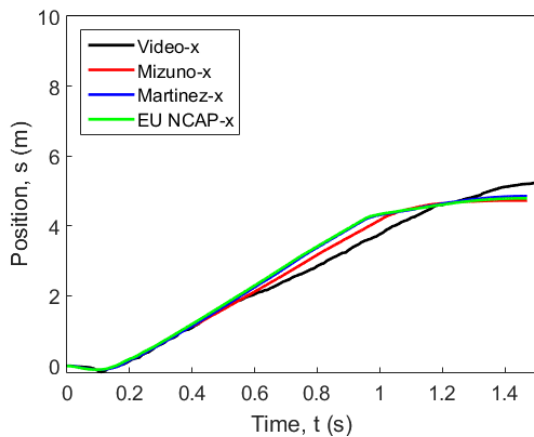
(b) Head marker-z T1



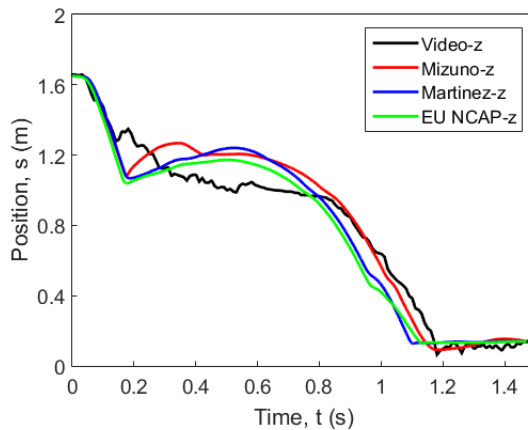
(c) Head marker-x T2



(d) Head marker-z T2



(e) Head marker-x T3



(f) Head marker-z T3

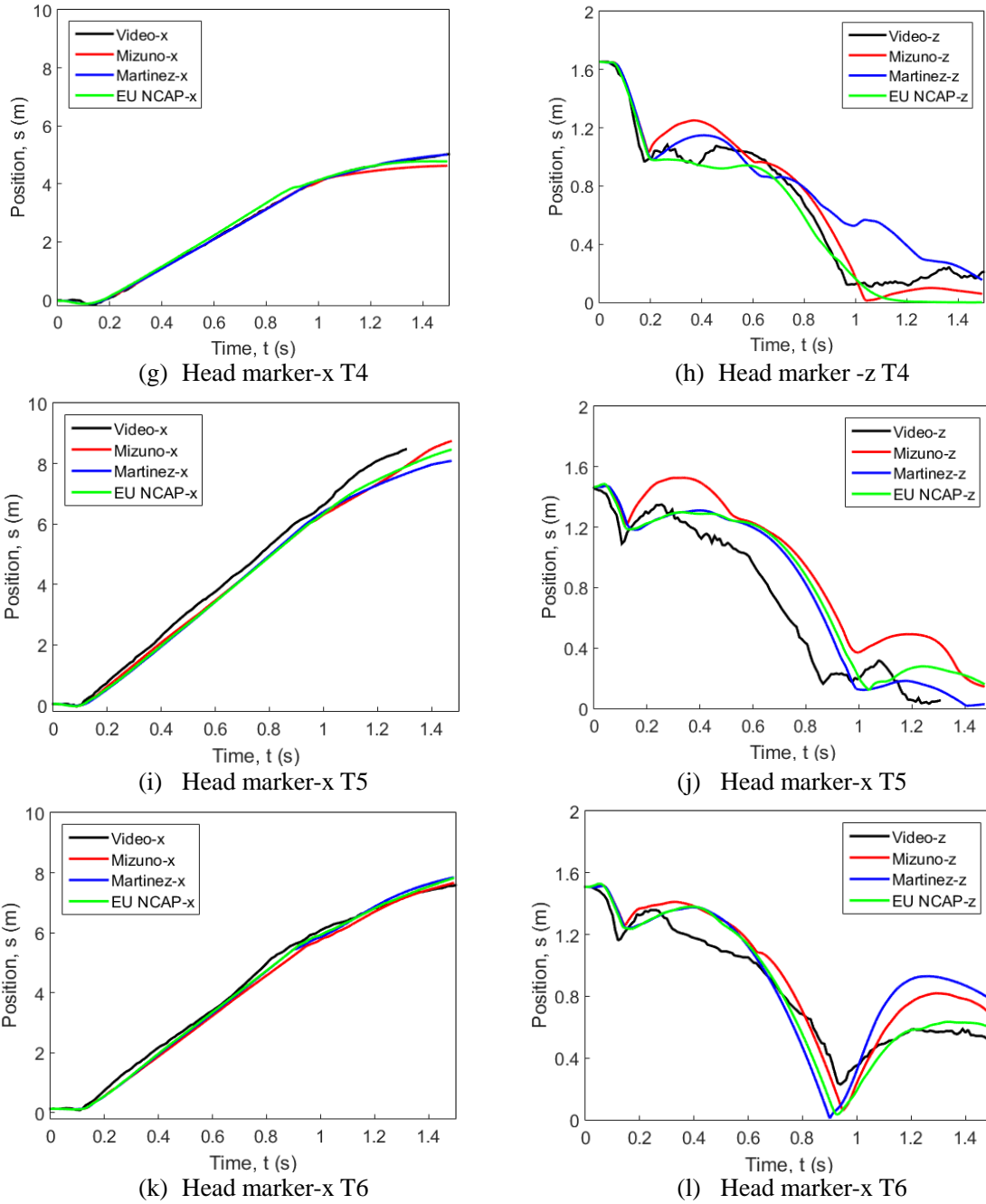
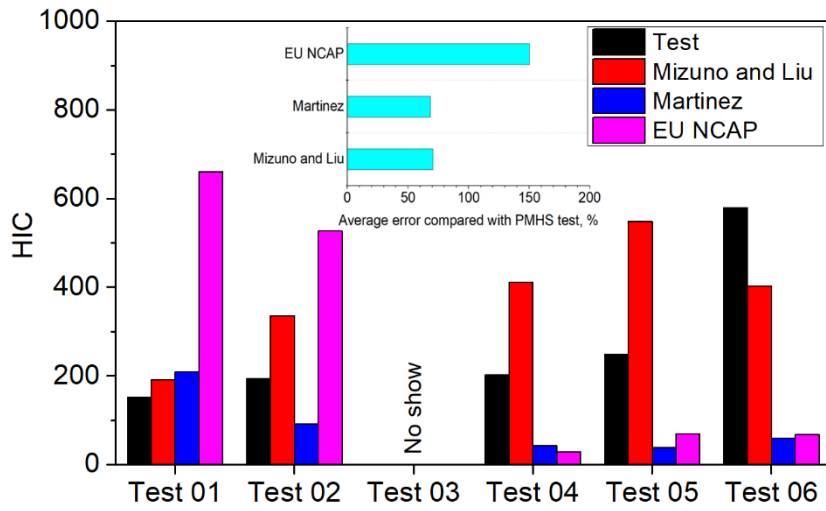


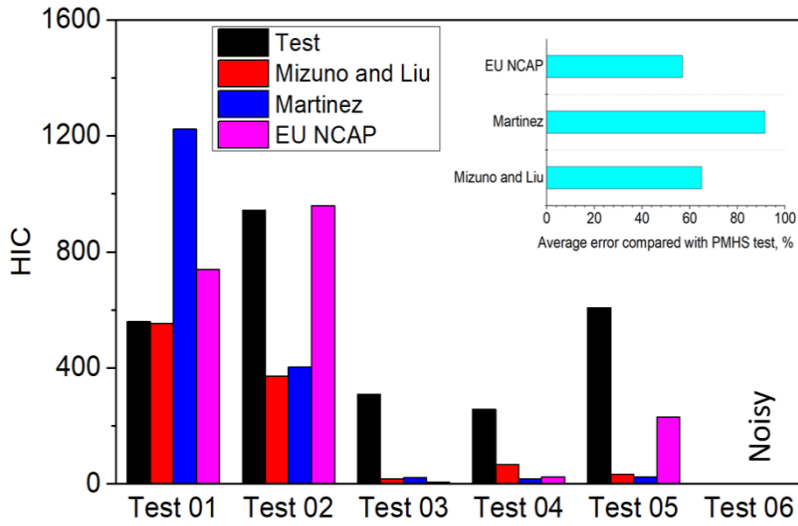
Figure 8 Comparison of pedestrian forehead trajectories between cadaver experiments and simulations

260 **3.3. Pedestrian head injury criteria assessments**

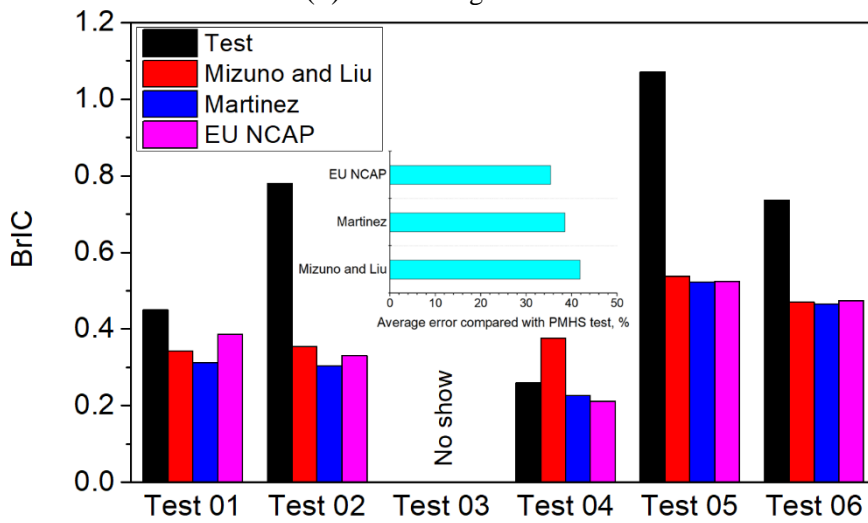
261 The *HIC* and *BrIC* scores were calculated for both vehicle and ground contact for all six cases and
 262 compared with the staged PMHS test results, as shown in Figure 9. The average errors for the injury
 263 indices for both vehicle and ground contact over all six tests obtained from simulations using vehicle
 264 contact characteristics from Mizuno and Liu, Martinez and EU NCAP compared with the cadaver
 265 tests are 51.3%, 62.0%, 73.3%, respectively.



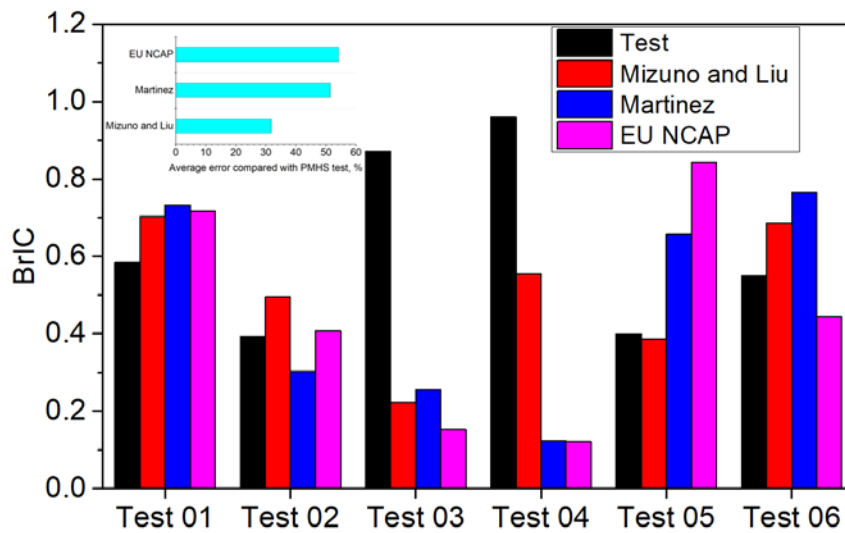
(a) *HIC* from vehicle contact



(b) *HIC* from ground contact



(c) *BrIC* from vehicle contact



(d) *BrIC* from ground contact

Figure 9 Comparison of head injury indices from vehicle and ground contact

267 **4. Sensitivity study**

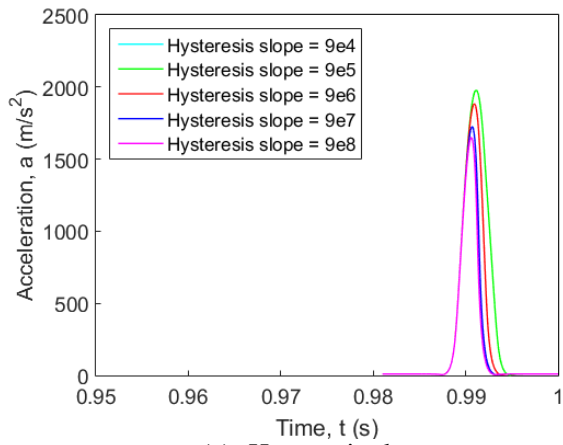
268 The vehicle contact characteristics do not obviously affect the kinematics during the vehicle contact.
 269 However, Section 3.3 shows they do have a large influence on the secondary ground contact and the
 270 resulting injury predictions. The influence of the pedestrian initial joint angles and internal damping
 271 of the MADYMO pedestrian model are also of interest. In these sensitivity studies, the Mizuno and
 272 Liu's stiffness was used as the baseline for comparisons as this stiffness gave the smallest overall
 273 error, see Figure 9.

274

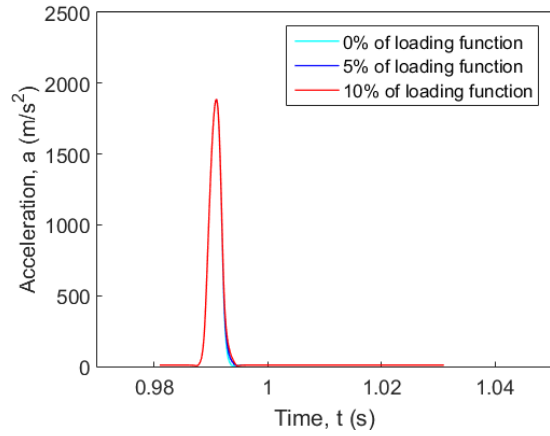
275 **4.1. Sensitivity study of hysteresis and unloading curve**

276 Apart from the loading function, the hysteresis slope and unloading curve definitions in MADYMO
 277 further influence the contact modelling. The effects were tested based on the simplified head model
 278 impact simulations. The hysteresis slope over 5 magnitudes (9e4, 9e5, 9e6, 9e7 and 9e8) and the
 279 unloading curves in 3 different ratios (0%, 5% and 10%) of loading curve were tested, see Figure 10.
 280 Results showed that lower hysteresis slopes produced relatively higher acceleration peaks and wider
 281 waves which can greatly impact *HIC* scores. Altering the unloading curve showed a negligible effect
 282 on the peak and impact time duration.

283



(a) Hysteresis slope



(b) Unloading curve (hysteresis slope = $9e6$)

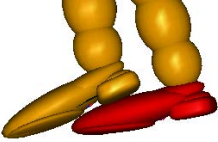
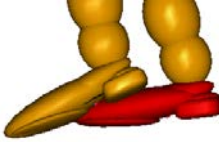
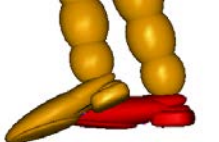
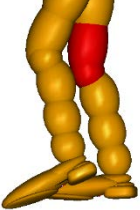
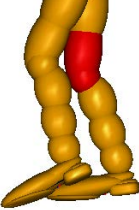
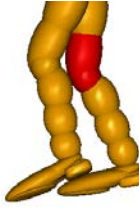



Figure 10 Testing of hysteresis slope and unloading curve effect on the contact using a simplified sphere model

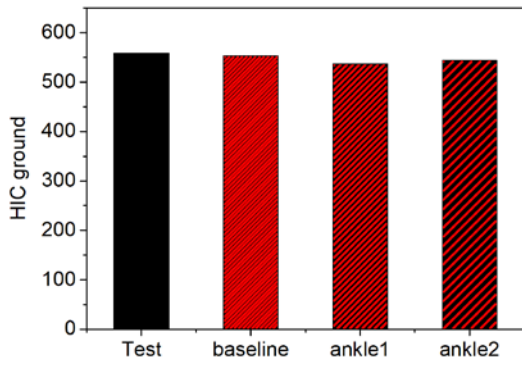
285

286 **4.2. Sensitivity study of pedestrian initial joint angle**

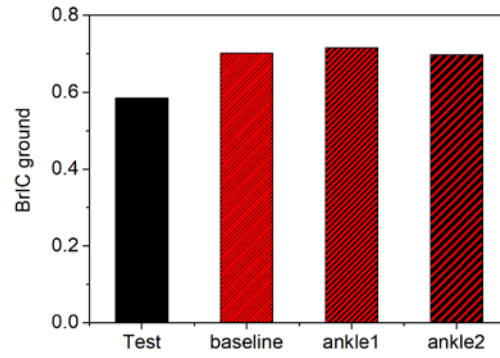
287 The initial joint postures of the MADYMO pedestrian model were set based on the measurement of
 288 the joint angles of captured images in different views of the cadavers just before testing (Shang *et al.*
 289 2020b). The effect of the joint angles was studied to assess the influence of joint angle on the
 290 resulting kinematics. Considering Test 01, the initial hip angle, knee angle and ankle angle of the
 291 struck leg were changed ± 5 degrees in YZ plane (see Table 4) to check the influence on the ground
 292 related head injury indices. Only one parameter was changed each time and the other two were kept
 293 constant (baseline) for this sensitivity study. The results are shown in Figure 11. The injury indices
 294 obtained from the baseline model and the pedestrian with initial joint angle 2 (as illustrated in Table
 295 4) are close while for the pedestrian with initial hip joint angle 2 and knee joint angle 2, the injuries
 296 showed noticeable differences when compared with the baseline results, as did the ground contact
 297 mechanisms, see Figure 12.

Table 4 Initial angles of joint sensitivity study

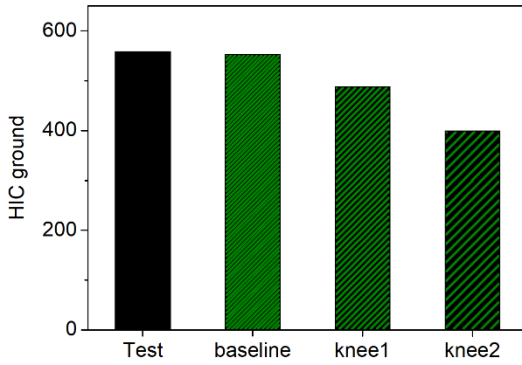
Joint	Angle 1 (-5°)	Baseline angle (°)	Angle 2 (+5°)
	2	7	12
Ankle			
	21	26	31
Knee			
	-5	0	5
Hip			



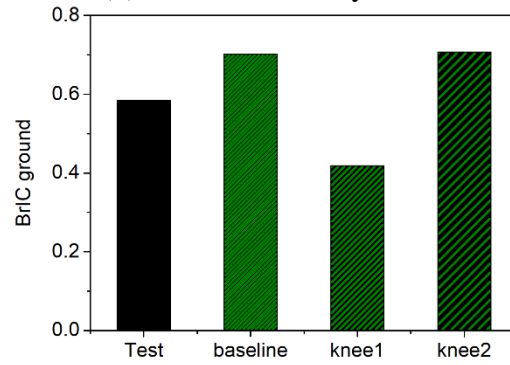
(a) Ankle sensitivity for *HIC*



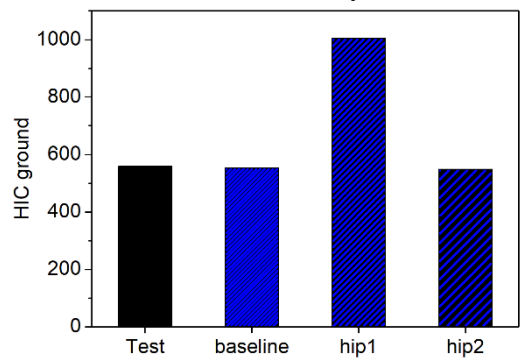
(b) Ankle sensitivity for *BrIC*



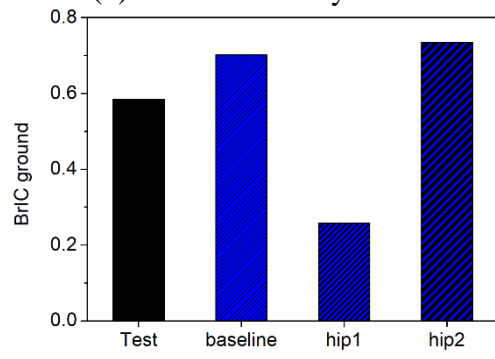
(c) Knee sensitivity for *HIC*



(d) Knee sensitivity for *BrIC*



(e) Hip sensitivity for *HIC*



(f) Hip sensitivity for *BrIC*

Figure 11 Initial joint angle effect on *HIC* and *BrIC* from ground contact for Test 01

298

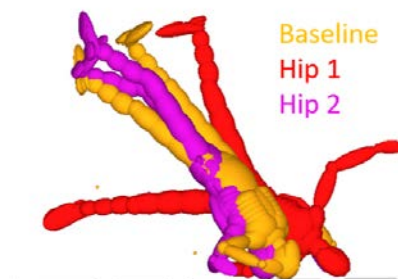


Figure 12 Pedestrian ground contact mechanisms in Test 01 from different initial hip angle from Table

299 **4.3. Sensitivity study of bending of pedestrian model**

300 As seen in Test 01 and Test 02 shown in Figure 7, the pedestrian model bounced off the vehicle after
301 the head windscreen impact, but this did not occur in the cadaver tests. A potential reason for the
302 excessive bouncing could be insufficient internal damping in the pedestrian models. A sensitivity
303 study of human model bending was therefore performed, with a modified a damping coefficient of
304 100 N·s/m used to reconstruct Test 01 and compared with the baseline simulation (almost no
305 damping), see Figure 13. The damping added to the model did not significantly reduce the rebound
306 but did significantly change the post-impact kinematics and the mechanism of ground contact.
307

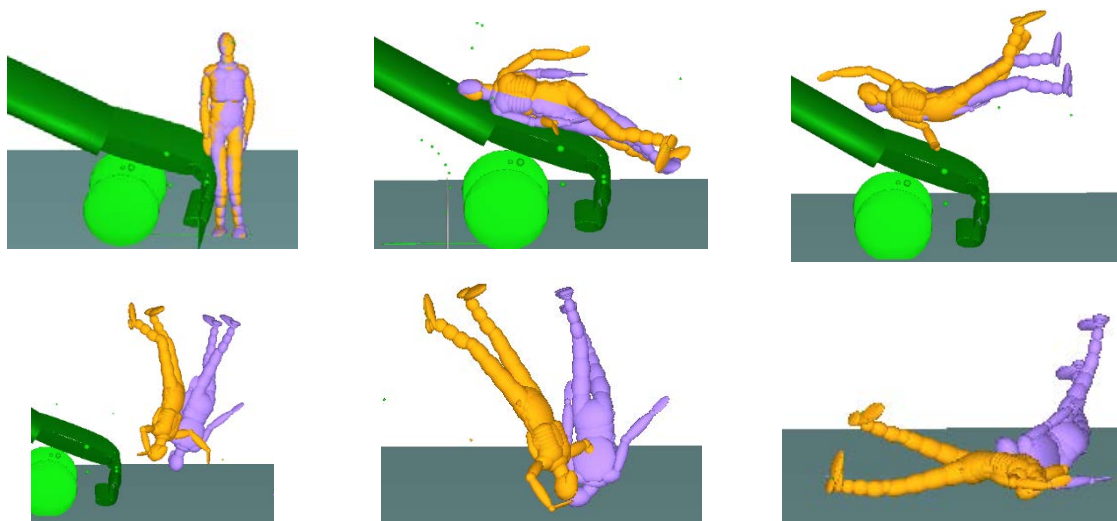


Figure 13 Sequence of baseline pedestrian model (orange) and the model with added damping kinematics (purple) in vehicle crash for Test 01

308

309 **5. Discussion**

310 This paper presents the first kinematics assessment of a multibody pedestrian impact model for the
311 phases following vehicle impact up to and including the ground contact, using cadaver test data for
312 comparison.

313

314 A computational model for assessing pedestrian ground contact injuries, and for possible use in the
315 development of ground contact injury prevention countermeasures, has a number of hierarchical
316 requirements. In terms of whole-body kinematics, there is the need for replicating the main body
317 segment trajectories following the initial vehicle contact, followed by the pre-impact pose and

318 velocity for the ground contact, especially the head. Subsequently, replicating the 6 DOF motion of
319 the head and other body segments during ground contact is needed for injury criteria evaluation. For
320 finite element models, tissue level stress/strain responses can be assessed, but this is beyond the
321 scope of the current paper which focuses on the evaluation of the multibody MADYMO ellipsoid
322 pedestrian model.

323

324 Table 3 shows that the timings of the head to vehicle contact are well reproduced for Test 01 and Test
325 02 of Shang et al 2020, where the collision speed is 30 kph and the normalized bonnet leading-edge
326 height is 0.7. However, for the 20kph cases (Tests 03 and 04) and the two high bonnet cases at 30
327 kph (Tests 05 and 06), there are substantial differences (of the order of 20 ms) in the head to vehicle
328 contact times. For Tests 01 and 02 the models separate from the vehicle too early, showing evidence
329 of insufficient energy absorption. However neither varying the contact characteristics nor introducing
330 additional damping was successful in addressing this. The timing of the subsequent ground contact is
331 poor in some cases (maximum error is 0.9s in Test 05, see Table 3-5, the arm of the pedestrian model
332 prevented the head impacting the ground) but the correspondence to the pedestrian ground contact
333 mechanisms identified by (Crocetta *et al.* 2015) is reasonable (correct mechanism identified in three
334 cases, incorrect in one case, and partially correct in two cases. However, Figure 7 shows some
335 substantial differences in the flight trajectory and ground contact sequences. In consequence it is not
336 surprising that the resulting injury criteria assessments in Figure 9 show cases where very substantial
337 differences between the model and the corresponding experiment are evident. Thus the current
338 MADYMO pedestrian models cannot reliably distinguish the influence of the various factors varying
339 between the different tests (vehicle shape and speed, body size and pose, vehicle contact
340 characteristic).

341

342 The sensitivity studies show that the choice of vehicle contact characteristic makes a significant
343 difference to pedestrian ground contact kinematics and injury evaluations, as do the hysteresis slope
344 and the initial knee and hip angles. Somewhat surprisingly, the contact characteristic using the older
345 data from impactor tests by Mizuno and Liu generally yielded the lowest errors for *HIC* in the
346 vehicle contact (Figure 9a), but the reliability of the resulting ground contact *HIC* is poor (Figure

347 9b). Similarly, the predictions of the *BrIC* in both the vehicle and ground contacts are a poor match
348 to the experimental data.

349
350 Increasing the internal damping in the pedestrian model does affect the kinematics but did not
351 improve the comparison with the experimental data. A further round of simulations was conducted
352 with the goal of improving the match between the predicted and test ground impact mechanisms by
353 changing the vehicle contact stiffness. The results are not presented here, but the outcome was that
354 while this approach was successful in improving the ground contact kinematics, the resulting vehicle
355 contact injury predictions were very different to the experiments.

356
357 Accordingly, future work must focus on amendments to the MADYMO pedestrian model to improve
358 its predictive capacity and ground contact, and on assessing the predictive capacity of other
359 multibody and finite element model formulations (Maeno and Hasegawa 2001, Iwamoto *et al.* 2003,
360 Untaroiu *et al.* 2016). This is needed before the model can be confidently applied to assess ground
361 contact injury countermeasures (for example about technology or vehicle front shape changes).
362 Similarly, it is clear that the MADYMO pedestrian model currently has limited potential for
363 application to individual collision reconstruction purposes, though there have been substantial
364 applications of this in the literature (Shen and Jin 2008).

365 366 **6. Limitations**

367 There are several limitations to this study. Firstly, the experimental data is based on cadaver testing
368 and it is understood that a living human response would be different, especially for the two 20kph
369 tests where voluntary motion is likely to play a significant role. Only one pedestrian model
370 formulation was assessed, and it is possible that a different multibody or a finite element model
371 would perform better. The models were globally scaled based on height and mass, not as an
372 individual body segment level. The experimental measurements of the pre-impact joint angles of the
373 cadavers were not precisely known.

374 375 **7. Conclusions**

376 We have presented the first assessment of a computational model (here the MADYMO ellipsoid

377 multibody pedestrian model) for predicting pedestrian flight and ground contact following a vehicle
378 collision. A comparison with six cadaver tests performed over the speed range 20-30kph and with
379 three different vehicle types and pedestrian sizes showed good capacity to predict vehicle contact
380 times, but differences between the models and experiments manifested prior to vehicle pedestrian
381 separation, and resulted in considerable differences in the ground contact kinematics. The resulting
382 head injury predictions based on the ground contact *HIC* and *BrIC* scores showed limited capacity of
383 the model to replicate individual experiments. Sensitivity studies showed substantial influences of
384 the vehicle- pedestrian contact characteristic and some of the initial pedestrian joint angles on the
385 subsequent ground contact injury predictions. Further work is needed to improve the predictive
386 capacity of the MADYMO pedestrian model for ground contact injury predictions.

387

388 ***Acknowledgement***

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390 support of the China Scholarship Council (CSC) is highly appreciated.

391

392

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394

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486

Table A1 Summary of tests performed in (Shang et al. 2020a)

Test number	Vehicle model	Vehicle speed (km/h)	Pedestrian age (y/o)	Pedestrian sex	Pedestrian height (m)	Pedestrian mass (kg)	NBLEH
Test 01	Peugeot 307	30.5	88	Male	1.74	66	0.7
Test 02	Peugeot 307	30.4	83	Male	1.72	69	0.7
Test 03	Citroen C4	20.4	94	Male	1.67	64	0.9
Test 04	Citroen C4	21.0	83	Male	1.67	55	0.9
Test 05	Renault Kangoo II	30.1	94	Female	1.58	38	1.2
Test 06	Renault Kangoo II	30.4	86	Male	1.62	69	1.1

490

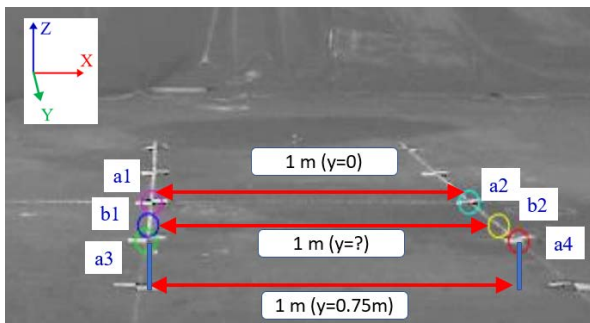
491 **Appendix B: Steps of defining and validating the movement input of the MB vehicle models**

492

493 (1) According to the width of the vehicle and the markers on the lab ground, using ginput
494 function in Matlab to pick 2 pairs of points (a1 and a2, a3 and a4) which define 1 m in $y=0$
495 and $y=0.75$, then the scale (the length of b1b2, the coordinates of b1 and b2 are in line with
496 the coordinates of the reference points picked from the side of the vehicle) can be calculated
497 based on the mathematical relation, see Figure B1 (a). The scale in Y direction depends on
498 the coordinates of the points P1 and P2 in Figure B1 (b).

499 (2) P1 is a reference point which can be used to find the tracking point P0 based on their relative
500 positional relationship. Pick two points P1 and P2 in a line on the side of the vehicle, then the
501 angular change of the vehicle can be calculated.

502



(a) Demonstration of choosing the scale



(b) Demonstration of choosing the tracking point P0

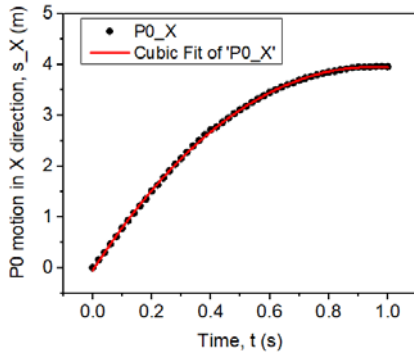
Figure B1: The steps of choosing the tracking point

503

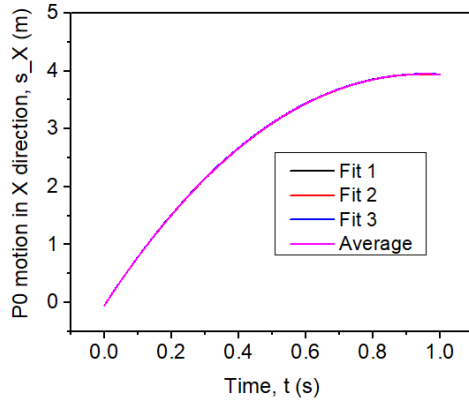
504 After the X and Z motion of the tracking point and the angle of the vehicle were calculated, the
505 polynomial fittings (third-degree polynomial for X motion, ninth-degree polynomial for Z motion,
506 fourth-degree polynomial for vehicle angle. Different orders were used for respective best matching
507 of the fitting curve) were applied to fit the time history curves to ensure a smooth MB vehicle
508 movement. Take Test 01 for instance, the motion of the tracking points corresponding the fitting
509 curves are shown in Figure B2 (a), (c) and (e). It should be noted since the changes in the Z direction
510 and theta (vehicle angle) are very small, a minor difference can result in relatively big errors when
511 tracking the points P1 and P2. To reduce the error, the movements were tracked three times and

512 averaged for each test, see Figure B2 (b), (d) and (f).

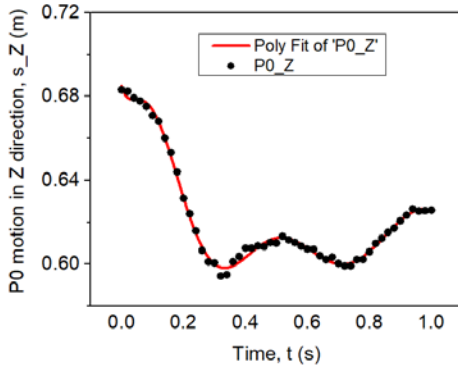
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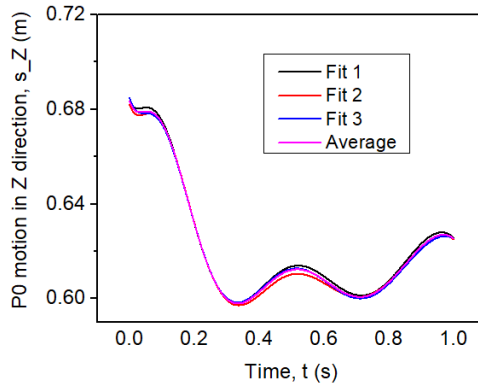
(a) Vehicle X motion



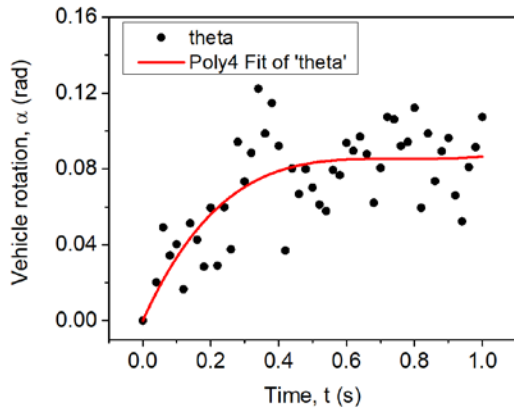
(b) 3 fitting curves of P0 X motion as well as the average curve



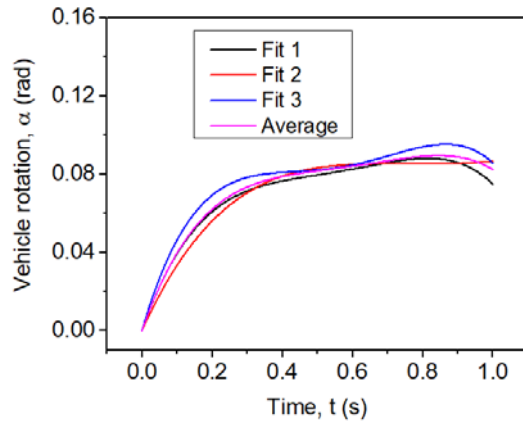
(c) Vehicle Z motion



(d) 3 fitting curves of P0 Z motion as well as the average curve



(e) Vehicle angle



(f) 3 fitting curves of vehicle angle as well as the average curve

Figure B2: The fitting curves of the motion of the tracking point

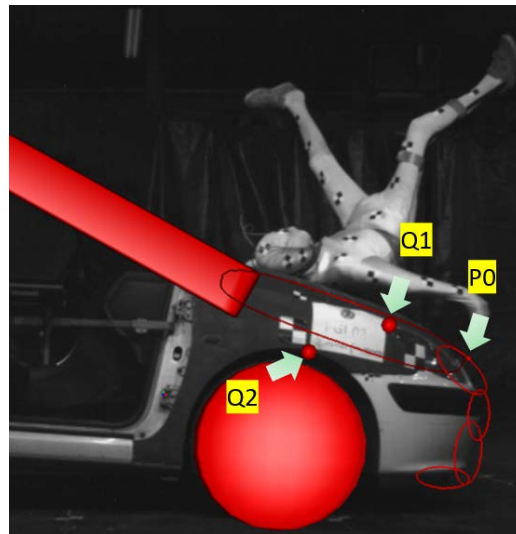
514

515 The input and output motions of the tracking point P0, as well as two other checking points Q1 and

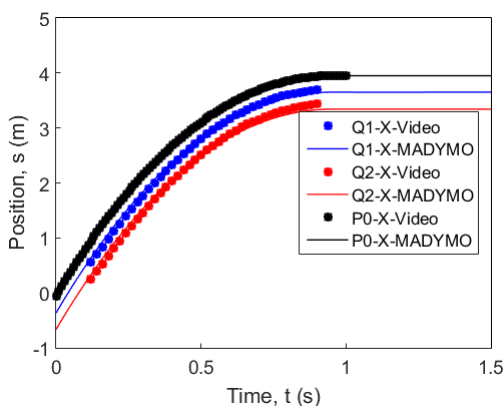
516 Q2 [as demonstrated in Figure B3(a)], were compared to check whether the MB vehicle model

517 moves as well as the input motions. Figure B3 (b) and (c) show that the movement of the tracking
 518 point P0 and the input is identical. For the two other reference points, the horizontal motion obtained
 519 from the video of the test and motion obtained from the MADYMO simulation output is closely
 520 related. The differences in vertical direction were small (up to 3 cm) and may be due to the vehicle's
 521 rotation angle, which can be ignored. The checking point results indicate the feasibility of using the
 522 tracking system to capture the vehicle movement.

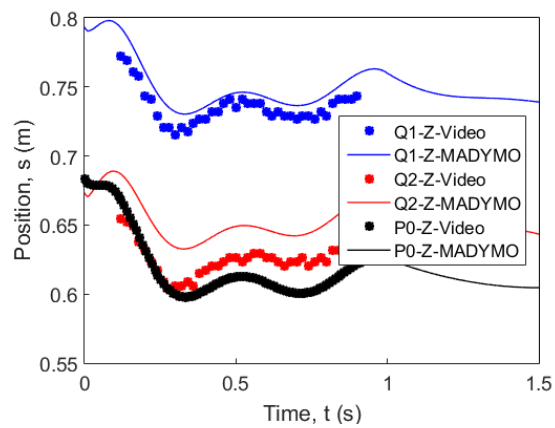
523



(a) The locations of two checking points



(b) X motion



(c) Z motion

Figure B3 The comparison of input and output motions of checking points

524