Interdisciplinary further development of an optimised anthropomorphic pedestrian surrogate for full-scale crash tests

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Abstract

Over the last seven years the Institute of Forensic Medicine of the Charité Teaching Hospital in Berlin has carried out post mortems on the majority of people killed in road accidents. In addition it has also conducted standardised radiological examinations of road fatalities using multi-slice computerized tomography (MSCT). Over more or less the same time the police in Berlin has been recording serious accidents with as much thoroughness as is usually reserved for crime scenes. When it comes to fatal accidents specially trained police officers are often supported by expert accident investigators. This has led both to collecting comprehensive accident data and related information regarding injuries and to establishing correlations. These findings have been used to improve the anthropomorphic test dummy (ATD). Engineering Consultants Priester & Weyde, Germany, had developed the first two ATD prototypes which can be used in crash tests to reproduce realistic damage to vehicles. The new version allows damage to occur also on the dummy which can provide insights into expected injuries on pedestrians and in future perhaps even help determine injury probabilities. This new version of the ATD has already been used in several crash tests, some of which reconstructing real accidents. Crashtest-Service.com of the University of Zilina in Slovakia and the Police in the Netherlands were amongst those who cooperated in carrying out some of these reconstructions using the new version ATD. This paper will be split into three parts: First some of the crash tests results will be provided, then the current status of ATD development will be presented and lastly some medical details regarding CT findings of fatally injured road users which have had considerable bearing on the development of the ATD will be discussed. However, the main focus of the paper will be on the technical development and use of the ATD as a surrogate for pedestrians and cyclists in full-scale crash tests.

Interdisziplinäre Weiterentwicklung eines optimierten biofidelen Dummys als Fußgänger Surrogat bei Full-Scale Crashtests

In den letzten 7 Jahren wurde im Institut für Rechtsmedizin an der Charité Berlin der Großteil der getöteten Verkehrsunfallopfer nicht nur obduziert, sondern standardisiert unter Verwendung eines Multislice Computertomographen (MSCT) radiologisch untersucht. Seit etwa derselben Zeit werden schwere Verkehrsunfälle in Berlin von der Polizei in einer Qualität aufgenommen, wie man es sonst nur bei Verbrechenstaten kannte. Hierzu werden die speziell ausgebildeten Verkehrspolizisten bei Unfällen mit getöteten Personen des Weiteren von Unfall-Sachverständigen unterstützt. Hierdurch konnten einerseits umfangreiche Unfalldaten und damit einhergehende Verletzungsinformationen erfasst und anderseits in Korrelation gebracht werden. Diese Erkenntnisse wurden bei der Weiterentwicklung des biofidelen Dummys (BD-Dummy) berücksichtigt, damit dieser nicht nur wie bei den zuvor im Ing.-Büro Priester & Weyde entwickelten ersten beiden Prototypversionen des BD-Dummy realistische Schäden an den Fahrzeugen bei Crashversuchen erzeugt, sondern auch solche Schäden am Dummy verursacht werden, die Aufschluss über zu erwartende Verletzungen bei Fußgängern geben bzw. die Verletzungswahrscheinlichkeit in Zukunft ggf. bestimmen lassen könnten. Der weiterentwickelte BD-

Dummy wurde bereits in mehreren Crashversuchen eingesetzt, bei denen unter anderem auch Realunfälle nachgestellt wurden. Die Unfallnachstellungen in Form von Kollisionsversuchen unter Verwendung des weiterentwickelten BD-Dummy erfolgten zum Teil in Kooperation mit Crashtest-Service.com, der Universität Zilina und der Polizei in den Niederlanden. Im Rahmen des Vortrages, der sich in drei Teile gliedert, werden einerseits einige Ergebnisse aus den durchgeführten Crashversuchen dargestellt und andererseits der aktuelle Entwicklungsstand des BD-Dummy präsentiert. Ferner werden die Erkenntnisse aus den computertomographischen Untersuchungen von getöteten Verkehrsunfallopfern, die einen erheblichen Einfluss auf die Entwicklung des BD-Dummy hatten, von medizinischer Seite vorgestellt. In diesem Paper wird allerdings vorrangig die technische Entwicklung und Anwendung des biofidelen Dummys als Surrogat für Fußgänger und Radfahrer bei Full-Scale-Crash-Tests dargestellt.

Introduction

Since 2010 there have been a number of degree theses [1] [2] [3] [4] [5] [6] (looked after by Priester & Weyde) which have contributed to the on-going development of the anthropomorphic test dummy (ATD) which is used as a surrogate for vulnerable road users as part of forensic reconstructions of car/ pedestrian and car/ cyclist collisions [7]. Comparisons with the University of Zilina‘s dummy used predominantly for forensic crash test reconstructions have shown that this improved ATD does not only achieve similar throw distances but also creates much more realistic looking damage to vehicles involved in a crash [8].

Right from the start the Institute of Forensic Medicine at Berlin's Charité has been involved in the on-going development of the ATD as it is there that the majority of Berlin's road fatalities have been examined using CT scanning at the behest of the investigating authorities. Post mortem CT examinations (pmMSCT) have been carried out using a 16-part Toshiba Activion multi slice scanner (Toshiba Medical Systems GmbH Neuss, Germany) with a slice thickness of 0.5 mm and a slice overlap of 0.3 mm. In agreement with the investigating authorities these scans are now standard when it comes to investigating fatal road traffic accidents.

Alongside traditional types of examinations pmMSCT constitutes an excellent additional tool which fully meets strict requirements in terms of objective and accurate documentation of findings and evidence. This non-destructive procedure takes place before any autopsy which is both manipulative and destructive. Unlike the examination subject itself, resulting data are available for years to come and can continue to shed light on questions which might arise at a later stage. They also offer numerous possibilities in terms of recording injury data and documenting and illustrating injuries as well as providing information for interdisciplinary accident reconstructions. Fracture patterns and bone dislocations allow conclusions regarding direction and intensity of impact, illustrated by a tibia fracture after collision with a car by way of an example (see Figure. 1).

Figure. 1: Primary contact point illustrated by a wedge-shaped fracture of the lower leg (left tibia after being hit by a car) using pmMSCT.

As lately injuries have been systematically recorded in a database while all personal data have been anonymised. Alongside the usual characteristics and characteristic values for general accident statistics the database also records impact-related forces to the body at the actual injury site. This has become possible because nowadays there are usually accident analysis reports for the accidents in question. This allows simulating contacts with vulnerable road users using multibody systems in PC Crash [9]. In future this might allow derivation a correlation between the forces at the time of impact and the type, site, direction and intensity of the resulting injuries suffered by victims of road traffic accidents.

Results of pmMSCT scans are already taken into consideration in accident analysis. Particularly when it comes to reconstructing real life accidents it is possible to compare CT scans with the damage on a dummy provided the dummy used as surrogate for the injured or perhaps killed road user is similar in built and material characteristics such as strength and elasticity.

Dummies currently used by the automotive industry are mainly employed to measure biomechanical properties and are not meant to suffer permanent damage in crash tests. Due to their design these dummies are not all useful to create realistic damage on a vehicle when used as pedestrian or cyclist surrogates in crash tests nor do they show any injuries which would be similar to those expected in humans under the same impact conditions [10].

Therefore it is necessary to come up with an affordable and above all life-like dummy which can also be used in forensic crash tests. Based on degree theses of university students such a dummy has been developed and tested by Priester & Weyde, Berlin. The aim was to recreate vehicle damage that was as realistic as possible in order to be able to use the damage patterns later as a reference in the reconstruction of the accident. On-going developments of this dummy now aim at simulating injuries on the pedestrian by creating equivalent damage. Crash tests have already been carried out in order to determine and test the suitability of this anthropomorphic dummy. The resulting data were compared with results from the available literature [11] [12] [13] [14].

Development of the optimised ATD

The biofidelic dummy by Priester & Weyde ("BD-Dummy" or anthropomorphic dummy, ATD for short) takes the 50 percentile male as reference. It measures 175 cm and has a mass of 78 kg. The most current generation has seen considerable changes to the ATD's skeleton aligning it much more closely with the anatomy of a human skeleton [6]. Whilst the early generations of the ATD reconstructed bone structures from wood today's bones are made from multi component materials with the advantage of generating reproducible results (unlike wood due to its fiber structure and therefore anisotropic properties). After comprehensive literature searches regarding actual bone strength and biomechanical properties of bone tissue a composite material was tested and developed to serve as a replacement for human bone material [5]. Other than the fracture behaviour of the material also the shape and dimensions played an important role in the development of the ATD. Based on available data a suitable 3D bone model was designed and dimensioned utilising the characteristics of the new bone replacement material (see figure. 2).

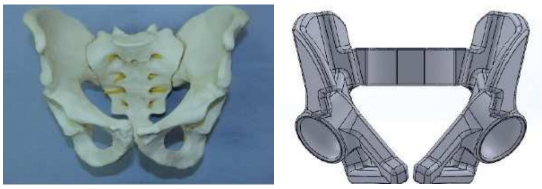


Figure 2: Anatomical pelvis vs. dummy pelvis [4].

A mix of epoxy resin and aluminium powder was used as bone replacement material. Unlike old dummy replacement bones made of wood, the new material has the advantage of being cast into moulds, thus allowing to be fashioned into any shape. The new bones are much more sophisticated and true to life (see figure 3).

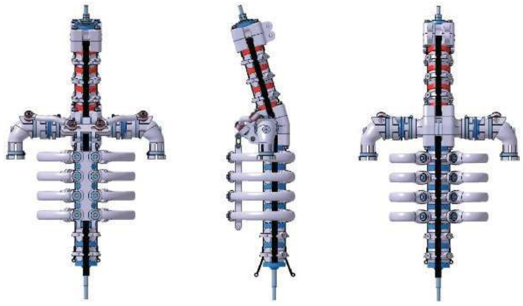


Figure 3: Anatomy of the upper body of the ATD [6].

Unlike wood, the new material also guarantees consistent manufacturing qualities which aids reproducibility. Furthermore any skeletal damage can be determined using CT scans instead of being forced to dismantle the dummy.

The tissue elements were also revised in terms of geometric shape and replacement material. Using multi component silicone it was possible to considerably increase the long-term durability of the ATD and to achieve a more realistic haptic. Types of silicone with different Shore hardness made it possible to reproduce body parts made from cartilage such as intervertebral discs which in turn means that the ATD's vertebral column shows very life-like flexibility. The fact that multi-component silicone is liquid is yet another added advantage as it allows more complex shapes to be manufactured. [4] [6].

A relatively stiff type of silicone was used as the material for the skeletal moulds. Manufactured parts can now be removed with minimum damage. 3D-positives necessary for manufacture were derived from the existing CAD model and printed using a 3D printer. The ATD's tissue parts are made using two different moulds. Smaller parts are fashioned from gypsum moulds whilst larger components are made using polystyrene moulds laminated with epoxy resin. The plan is to start using silicone moulds for these parts as well.

Creating a person-specific dummy

Other than creating a 50 percentile male it is also possible to individually adapt the ATD provided the anthropometric dimensions of the accident victim are known. These can be determined using CT scans. These scans can also be used to provide information about the skeletal dimensions and the positioning of the victim's joints which can later be used to define the skeletal design of the dummy. However, attention must be given to the fact that bones might break and move as a result of an accident. Hence the individual values must be estimated or derived from standardised sizes (*DIN 33402- Körpermaße des Menschen* – human body parts). Please see figure 4.

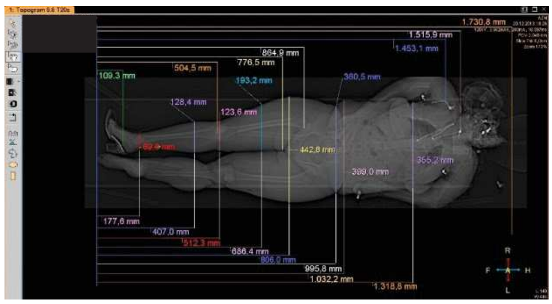


Figure 4: CT scan with measurements [15]

CT scans allow use of raw data to create image slices. Using these slices it is possible to determine the victim's mass distribution by having a CAD program recreate the various surfaces. Adding height gaps, which can also be derived from the scans, a dummy of a specific volume can be achieved which is very similar the actual person. Using a dummy material density that matches the average density found in human tissue allows a mass distribution of the dummy that corresponds to that of the actual person that was injured or killed in the accident. The slice can then be loaded as background to a CAD program and dimensioned so that technical drawings corresponding in scale can be directly created against this background. In the CAD program individual steps are recreated as elliptical bodies and their surface content is compared with CT data and adapted accordingly (see Figure 5).

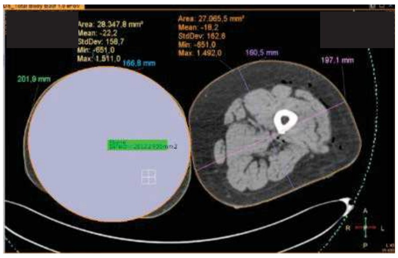


Figure 5: Picture of slice in a CAD program [15].

Therefore it is possible to use CAD to produce individual moulds for tissue parts. The individual cross sections are transferred to wooden boards which in turn are glued to polystyrene blocks. Heated wire is used to cut moulds from the polystyrene block. Specific tissue parts can then be cast using a two-component silicone and later attached to the dummy (see Figure 6).

Figure 6: Specific second generation dummy (here depicted without outer cover in order to illustrate the specific component tissue parts of the surrogate for a 163 cm female weighing 80 kg)

Tests with optimised ATDs

Several car to pedestrian and car to cyclist collisions have already been carried out to evaluate the optimised dummy's suitability as a surrogate for vulnerable road users in full-scale crash tests. Particularly when it comes to reconstructing actual accidents it is possible to compare damage that occurred in the accident with that of the crash vehicle in the reconstruction. By way of an example, the individual surrogate of a 163 cm female weighing 80 kg (see figure 6) was used as a cyclist in a crash test. It was hit with a vehicle speed of 100 km/h (rounded). Comparing photographs of the damage from the reconstructed crash with the damage caused to the vehicle in the real accident shows a close match not only in terms of throw distance but also in terms of specific damage patterns. However, there are also deviations which illustrate that the impact constellation must have been different and the collision speed probably even higher than originally assumed in the accident reconstruction.

Figure 7: Vehicle damage in the actual accident (upper photo) vs. reconstruction in a crash test (bottom photo) [15].

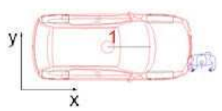
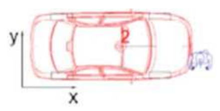
The first generation of ATDs had already been validated using an actual accident [11]. In this accident (made available by Engineering Consultants Rau/Leser/Strzeletz) the collision speed was known as the accident car had been equipped with EDR. During further tests as part of ATD validation it was also determined that the both the height of the individual as well the status of the vehicle's braking system significantly affect the position of the site of head impact [12]. This in turn led to the conclusion that wrap around distance (WAD) and longitudinal distance between the first impact at the car's front and the head impact do not constitute reliable criteria for narrowing down collision speed as the site of head impact does not solely depend on the speed at the time of collision. It also depends greatly on the specific shape and contour of the front of the vehicle. Therefore a simple comparison of WADs based on crash tests does not seem to be enough to narrow down collision speeds to a sufficiently reliable range without also considering braking-related deceleration and the resulting dipping of the front of the car, the actual shape of the vehicle and the height of the person with whom the car collided.

Also the further developed BD-Dummy, whose improvements have been mainly due to the work carried out by KNAPE [6], was also validated using the same actual accident. During this accident a Vauxhall Corsa B collided head-on with a pedestrian at a speed of 53 km/h after braking. During the symposium "Technical Analysis of Road Traffic Accidents" organised by the University of Žilina in Galanta, Slovakia a full-scale crash test reconstruction of this actual accident was carried out [16]. In addition another crash test at higher speed was staged in order to validate reliability and suitability of the improved ATD also at higher collision speeds of above 70 km/h. In this second crash test a Ford Mondeo Mark 2 was used as the crash vehicle.

Both test vehicles (Vauxhall Corsa B and Ford Mondeo Mk. 2) were equipped with several EDRs (version 1.3 and AT series) and an accelerometer by DSD (Type PicDAQ 5). 3-axis acceleration sensors by Gulf Coast Data Concepts were attached to the head and the overall centre of gravity of the dummy in order to measure accelerations in the dummy.

The vehicle type for Test 1 was carefully selected as this test was going to be a reconstruction of a real-life accident. The car had been equipped with EDR. So we know that the collision speed was around 53 km/h. There were also photographs showing the damage to the car. The second crash test was carried out to check the ATD's suitability for higher collision speeds (in this case 71 km/h, rounded). In the tests the pedestrian dummy was hit head-on by both vehicles with the impact being slightly offset to right of centre of the car. The dummy had no speed of its own and was hit from the right (see Table 1).

Table 1: Overview of the tests

	Test 1	Test 2
Impact configuration		
		
Car	Vauxhall Corsa B	Ford Mondeo Mk 2
Dummy	Optimised ATD-Dummy, 50%-tile male; 175 cm; 78 kg	
Speed	Vauxhall: 52.7 km/h; Dummy: 0.0 km/h;	Ford: 71.1 km/h; Dummy: 0.0 km/h;

In both tests the initial impact was with the dummy's legs. Then the ATD adapted to the contours of the car. This led successively to a notable change in speed of the upper thighs, the pelvis, the abdomen, the thorax as well the neck and the head of the pedestrian surrogate. In Test 1 the dummy's head impacted slightly to the right of the upper half of the windscreen. This caused the glass to crack causing the head to enter the passenger compartment. The left shoulder hitting the car's right A-column stopped the head from moving deeper inside the car. The dummy then propped itself up on the A-column and started to rotate across the car which in turn removed the head from the passenger compartment. This movement of the dummy was interrupted by the test vehicle starting to brake at that time causing the dummy to fall to the ground next to the car, roughly at the right wing mirror. The pedestrian surrogate only detached itself from the car after the second impact. Therefore there was no "flight" phase as part of this test (see figure 8).

Figure 8: Images from Test 1

Unlike in Test 1 the windscreen of the Ford Mondeo withheld the stress exerted by the head impact to the extent that it did not break completely. The start of the dummy rotating caused the upper body to become detached from the car. This led to the energy exchange between car and dummy happening mainly via the dummy's head which was pushed across the windscreen towards the edge of the car roof causing an oval spider crack on the windscreen. The legs of the ATD then rotated above head and thorax until the dummy had rotated by almost 180° along its coronal plane. Continuing rotation the dummy then became detached from the car and began the "flight" phase ca. 0.475 s after the initial impact. The pedestrian surrogate rotated alongside the right of the vehicle and finally hit the ground full-on around the rear right wheel (see figure 9).

Figure 9: Images from Test 2

Evaluation of dummy throw distances

After the tests the positions of the dummy's centre of gravity we recorded with positive x-values in longitudinal direction of the road and positive y-values against the dummy's gaze direction.

This resulted in the following throw distances for Test 1 (v_k = 52.7 km/h):

- Longitudinal throw distance: 16.0 m
- Lateral throw distance: -1.7 m
- Overall throw distance: 16.1 m

The results for Test 2 (v_k = 71.1 km/h) were:

- Longitudinal throw distance: 31.8 m
- Lateral throw distance: -1.8 m
- Overall throw distance: 31.9 m

The throw distances of both tests largely match the measured results from crash tests and real accidents based on BURG/MOSER [17] as well as tests with older ATD generations. However, further tests should be carried out at higher speeds in order to corroborate these statistics (see figure 10).

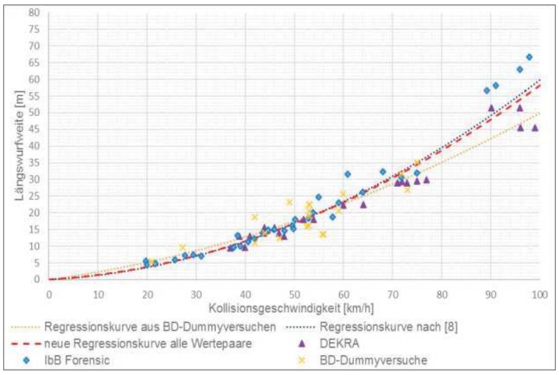


Figure 10: Longitudinal throw distances from real accidents, crash tests with various dummy types and the BD-Dummy with new regression curves according to [13] and [14]. (Also included as full-width graph at the end of the paper.)

Längswurfweite – longitudinal throw distance, Kollisionsgeschwindigkeit – collision speed, Regressionskurve aus BD-Dummyversuchen – regression curve from ATD crash tests, Regressionskurve nach [8] – regression curve acc. to [8], neue Regressionskurve alle Wertpaare – new regression curve, all value pairs, BD-Dummyversuche – ATD tests

Evaluation of dummy sensors

Using the acceleration values measured by the dummy sensors it was possible to analyse which values were achieved for the usual protection criteria during the tests. However, it should be pointed out that the actual protection criteria (HIC_{36}, a_{max} and $a_{3\,ms}$) cannot really be determined based on the measuring equipment used in the test as it does not meet standard requirements. Hence the protection criteria were calculated using only existing calculation methods and available acceleration values and the following protection criteria values should be considered only as a comparison.

For Test 1 (v_k = 52.7 km/h) when the head hit the windscreen the maximum comparative HIC_{36}-value was 188. This relatively low value should be due to the glass breaking which caused the dummy's head to enter the passenger compartment. Reviewing the videos also showed that the maximum acceleration of the head of a_{max} = 67.7 g and the highest acceleration of $a_{3\,ms}$ = 59.1 g averaged over three milliseconds occurred when the head hit the trim of the A-column. At that moment the head was pulled out of the passenger compartment by the beginning rotation of the dummy and, in doing so, got caught on the A-column several times. All calculated comparative protection criteria levels during the crash test with v_k = 53 km/h remain considerably below the limit values. It can be concluded that the head impact into the windscreen at a collision speed of approximately 53 kph had not yet led to a most likely probability of fatal injuries. The following values were calculated for the protection criteria relating to the thorax in Test 1: The dummy's primary impact resulted in a maximum upper body acceleration of a_{max} = 41.1 g and an acceleration of $a_{3\,ms}$ = 37.6 g averaged over three milliseconds. For the second impact on the road a_{max} was 49.2 g and a_{3ms} was 39.5 g. Analysing the ATD's thorax acceleration data shows that hitting the road caused more stress to the dummy's body that the primary impact of the head against the car. As was the case for the head the applicable protection criteria limits for the upper body were not exceeded for an impact at a speed of v_k = 53 km/h.

The values for derived protection criteria in Test 2 (v_k = 71.1 km/h) are as follows: The head impacting against the windscreen created a maximum head acceleration of a_{max} = 466.5 g and an a_{3ms}-value of 315.1 g. As was the case for the comparative HIC-value of 2042, all protection criteria levels in Test 2 by far exceeded the ones in Test 1. With a collision speed of 71 km/h all limit values were greatly exceeded. The maximum thorax acceleration of a_{max} = 30.7 g at the time of primary impact and of 54.8 g at the time of secondary impact show that the secondary impact on the road resulted in higher accelerations than the impact with the car. Accelerations averaged over three milliseconds of $a_{3\,ms}$ = 29.4 g for primary impact with the car and of $a_{3\,ms}$ = 48.7 g for secondary impact on road show that the stresses for the body are higher when hitting the road.

Comparing both tests it seems that collision speed has hardly any bearing on the thorax acceleration at primary impact. Reviewing the video shows that a higher collision speed causes the upper body to hit the bonnet less hard and instead it rather slides along or up until, after only a short time, it comes to head and shoulder impact with the windscreen. Nonetheless the higher collision speed leads to a greater speed change of the entire dummy resulting in much higher head stresses during primary impact with the car and much higher thorax stresses during secondary impact with the road when the speed is higher.

Evaluating damage to the dummy

Before determining whether the revised ATD is suitable in terms of matching dummy damage with injuries that can be expected in humans it was necessary first to document the damage occurred during the crash and to assign corresponding impact points on the car and on the ground. To this end, CT scans of the two dummies used in the tests were taken and in addition the dummy used in Test 1 was also dismantled and the damage documented (see figure 11 and Table 2).

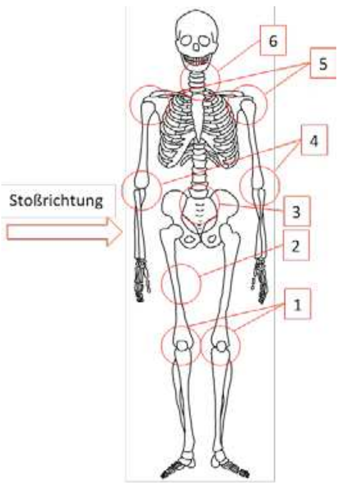


Figure 11: Dummy damage T1

(Stoßrichtung – direction of impact)

Table 2: ATD damage T1

	Dummy damage T1
1	Fractures to both lower legs around the knees
2	Facture of the right femur
3	Double fracture of the sacrum
4	Fracture of both elbows
5	Dislocation of both shoulders
6	Damage to discs in cervical spine

It was noted that in Test 1 (v_k = 53 km/h, rounded) both lower legs of the dummy were broken just under the knee joint. The video showed that these “dummy injuries” were due to contact with the front spoiler. Then the dummy hit the front edge of the bonnet of the Vauxhall Corsa with the right upper thigh (impact side) which caused the replacement femur to fracture (see figure 12).

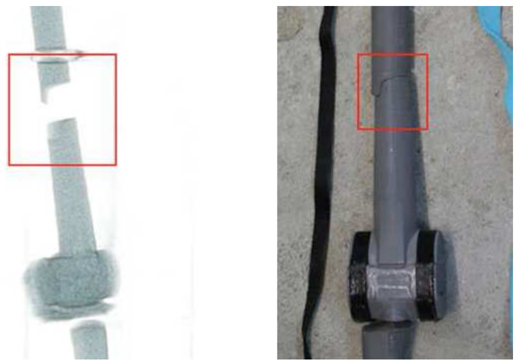


Figure 12: CT scan vs. exposed dummy femur.

Impact of the pelvis region with the bonnet led to multiple fractures of the pelvic bone. The dislocation of the left shoulder resulted from hitting the lower part of the crash car’s windscreen. Both arms were damaged around the elbows due to various impacts and the discs of the cervical spine (made from soft dual-component silicone) showed several tears, probably caused by severe flexing of the neck before and after the head impact.

By comparison the dummy used in Test 2 (v_k = 71 km/h, rounded) showed considerably more damage (see figure 13 and table 3).

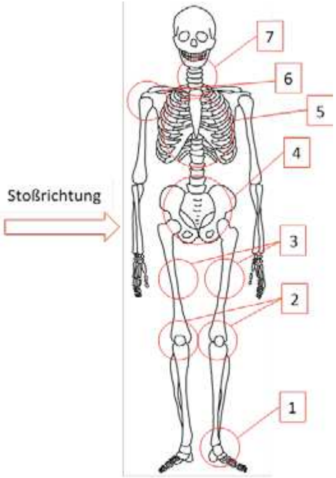


Figure 13: Dummy damage T2

(Stoßrichtung – direction of impact)

Table 3: ATD damage T2

	Dummy damage T2
1	Right foot torn off
2	Fractures to both lower legs below the knee joint
3	Fractures to both femurs
4	Multiple pelvis fractures
5	Multiple broken ribs
6	Fracture to the right shoulder joint
7	Damaged discs of the cervical spine

Assessing arm damage on the dummy was not possible as the dummy in Test 2 was later used for further tests. However, reviewing the video data led to the assumption that there was also damage to the arms caused by the Ford Mondeo travelling at 71 km/h at the time of impact. In any case, there was a fracture to the left femur (side away from the impact) due to the much harder impact against the front edge of the bonnet. In addition the dummy's thorax showed multiple broken ribs which are likely to be due to the harder secondary impact against the road. The impact speed of 71 km/h also caused the dummy to lose a foot during primary impact owed to the so-called "pull-under-effect". This effect can frequently be witnessed during actual road accidents and causes severe injuries to feet and lower legs. Contact with the lower edge of the front bumper can result in the foot being attached to the body by nothing else but skin and tissue (see figure 14) and even complete amputations are occasionally observed at higher collision speeds

Fig 13: Pull-under-effect with torn-off foot in the test, speed v_k = 71 km/h (above) and partially torn-off foot after real accident (below) [18].

Comparison: Crash test and real accident at 53 km/h

With a height of 171 cm and a weight of 73 kg the pedestrian in the road accident showed similar physical characteristics to the ATD that was used. Unlike in the test, the pedestrian was hit on the driver's side of the Vauxhall Corsa B. The reconstruction in the test was carried out as a mirror image of the road accident using front right so as to put the driver of the crash test vehicle in as little danger as possible. The throw distances in the road accident were 16 m in longitudinal direction and 2 m in lateral direction. The values are almost identical with those achieved in the crash test (longitudinal throw distance: 16 m; lateral throw distance: 1.7 m). The dynamic wrap around distances (WAD) are also a close match (accident: 240 cm; crash test: 230 cm). The crash test vehicle did not show any dent misalignment which can be explained by the position of the dummy's foot and by the pedestrian dummy not having a speed of its own. In the accident there was a dent misalignment of ca. 10 cm [19].

The windscreen of the accident car (left photograph in figure 15) shows two spider cracks on the driver side caused by shoulder and head impacts. The head hit the upper frame. The car in the crash test (right photograph, figure 15) shows a similar damage pattern. The shoulder caused a spider crack in the lower part of the windscreen. The head impact was ca. 10 cm lower compared to the real accident which explains why there was no damage to the frame of the windscreen. Instead the dummy went through the glass (see figure 15).

Figure 14: Car damage after the accident (left) [19] and after the crash test (right), speed: 53 km/h.

At the front of the accident vehicle there are wipe marks below the left headlight marked "(1)" in the left photograph of figure 16. The wipe marks were caused by the impact of the lower extremities. Looking at the vehicle after the crash test wipe marks where spotted in almost the same place (right photgraph, figure 16). Both cars also show an identation between headlight and grill, marked "(2)" in both photographs of figure 16. During the accident the glass of the left headlight of the green Vauxhall Corsa was destroyed and the bonnet warped. The test vehicle also showed a large indentation of the bonnet which does not seem quite as pronounced in the real accident judging by available phototgraphs (see figure 16).

Figure 15: Car damage 2: accident (left) [19] and crash test (right).

Comparing and contrasting damage patterns on both vehicles shows a great deal of similarities. The breakage patterns of the windscreens largely match other than the head impact being higher up in the real accident and the windscreen breaking in the crash test. The same is true for wipe and pressure marks in the area below the headlights on the impact side as well as the striking indentation on the front edge of the bonnets. There are differences in headlight damage because the accident car had old-style glass diffuser headlights while the headlights of the crash test vehicle were entirely made from plastic.

Measuring deformations using computer aided photogrammetry

Damage on the test vehicles in terms of position and intensity was recorded and analysed using three different measuring and documentation methods:

- Manual measurement of the deformation depth with a measuring stick
- Computer-aided photogrammetry with PhotoScan
- Laser scanner (Faro X 130 HDR)

Please note that only the maximum deformation depth was measured when using a measuring stick. The cars were photographed from various angles before and after the crash tests. PhotoScan can then be used to generate a three-dimensional point cloud which can be compared and contrasted with the reference point cloud created by the laser scanner. There were deviations of up to 6 mm when comparing the PhotoScan measurements with the reference point cloud. Measuring by hand gave a deformation depth of 16 mm vs. 18 mm when using the image-based point cloud of PhotoScan. This shows that deviations are quite small and that, generally speaking, point clouds created using PhotoScan are suitable for determining deformation depths. One disadvantage is that this system is of limited use when there is strong reflection due to direct and intensive sun light on the paint [14].

Summary

Since 2010 Engineering Consultants Priester & Weyde have been developing an anthropomorphic dummy (ATD) as a pedestrian surrogate for full-scale crash tests in co-operation with the Institute of Forensic Medicine of the Charité in Berlin as well as students of the Technical University (TU) of Berlin, the University of Applied Sciences (HTW) Dresden and the University of Zilina. Since 2017 this so called Biofidelic Dummy has been commercially produced by Crash-Test-Service in Münster, Germany. Right from the beginning of this development the focus has been on creating a dummy as a human surrogate which can cause realistic damage to vehicles in crash tests. In order to achieve this, replacement materials have been tested and even newly developed which, in terms of strength and elasticity, behave similarly to human bones as well as muscle and skin tissue. The design method for bones and joints mirrors the anatomy of the human body as closely as possible in order to allow, or limit, mobility in line with anthropomorphic characteristics and to create significant damage to the dummy equivalent to what would be expected for typical injuries to bones and joints in humans if they were exposed to the same impact conditions. To this end, several crash tests were carried out and analysed, some of which were forensic reconstructions of real accidents. Injuries suffered by pedestrians and cyclists killed in the real accidents could so be compared with the damage caused on the ATDs during reconstructions thus allowing further development of the ATD in order to achieve reproducibility by improving manufacturing quality and optimising biofidelity in terms of mobility and dummy damage. As part of diploma- and bachelor-thesesthese prototypes of the optimised ATD were produced, crash tested and evaluated for resulting vehicle damage and the ability to reproduce potential injuries as equivalent damage. The tests have shown that this ATD is extremely suitable as a pedestrian or cyclist surrogate in full-scale crash tests. It creates realistic damage to the test vehicles while showing very plausible damage on a par with injuries that can be expected when a person is hit by a car. Nonetheless, there are ideas for further improvements which will be realised through cooperation with technical and medical universities and the manufacturer. These ideas cover general recording of statistics and analysing evaluations of injuries incurred in real accidents and extend to reconstructing a few real accidents as part of forensic investigations involving a comparison of actual injuries with dummy damage based on these reconstructions. The aim is to develop an anthropomorphic dummy for use in standardised full-scale crash tests which can reproduce expected injuries in typical accident scenarios involving vulnerable road users, i.e. pedestrians and cyclists, showing equivalent damage in order to facilitate reliable statements regarding probable injuries – something that currently does not seem possible with currently available technically and medically dubious component tests (head and leg impactor tests). As expected evaluations of head and thorax accelerations in reconstructions with existing and tested ATDs show that secondary contacts with mostly hard road surfaces usually lead to much higher stresses on the ATD than the primary impact with the car. Hence using a suitable ATD as part of standardised full-scale crash tests might lead to quite different and efficient designs for active and passive protection of vulnerable road users.

In any case the damage generated in the improved third generation ATD can be considered plausible. The optimised ATD can simulate injuries to many regions of the body which are similar to the statistical injury distribution in car to pedestrian collisions by the dummy producing damage which corresponds to the respective injury sites on the body. Particularly injuries which usually occur at the lower extremities can be reproduced with damage occurring at the dummy's skeleton. Following leg impact against the front of a car dummies showed damage to the same regions as would be expected in humans involved in an equivalent collision.

Evaluating dummy damage and relating it to various impact sites on the vehicle and on the ground has also illustrated that "injuries" and damage to the dummy are mainly due to the vehicle parts which, based on statistics, are expected to cause these typical injuries. Due to its realistic impact behaviour looking at damage on the ATD might allow drawing conclusions regarding injuries and injury potential in humans when crash conditions are the same.

Available crash test results have shown that damage patterns on test vehicles largely match damage caused in real accidents in terms of type, scope, position and intensity. Particularly comparing real accidents with tests using the same type of car illustrates that damage patterns on the vehicles are a close match and as such test results can be considered realistic. Therefore the improved ATD can be considered particularly suitable for creating realistic damage patterns. Furthermore throw distances, both longitudinally as well as laterally, generated in a reconstruction matched the values which were measured in a well-documented real accident. Therefore the revised ATD is suitable for use in crash tests as a surrogate for vulnerable road users such as pedestrians and cyclists. Based on available tests it seems possible not only to compare and contrast damage patterns to vehicles but also dummy damage and skeletal injuries caused by the real accident so that in future statements can be made regarding injury potential when using this ATD. There will also be further evaluations of injuries and how they arose as part of interdisciplinary cooperation between forensic pathologists and accident analysts based on retrospective analysis of (usually well-documented) accidents with vulnerable road users which have occurred in Berlin since 2010.

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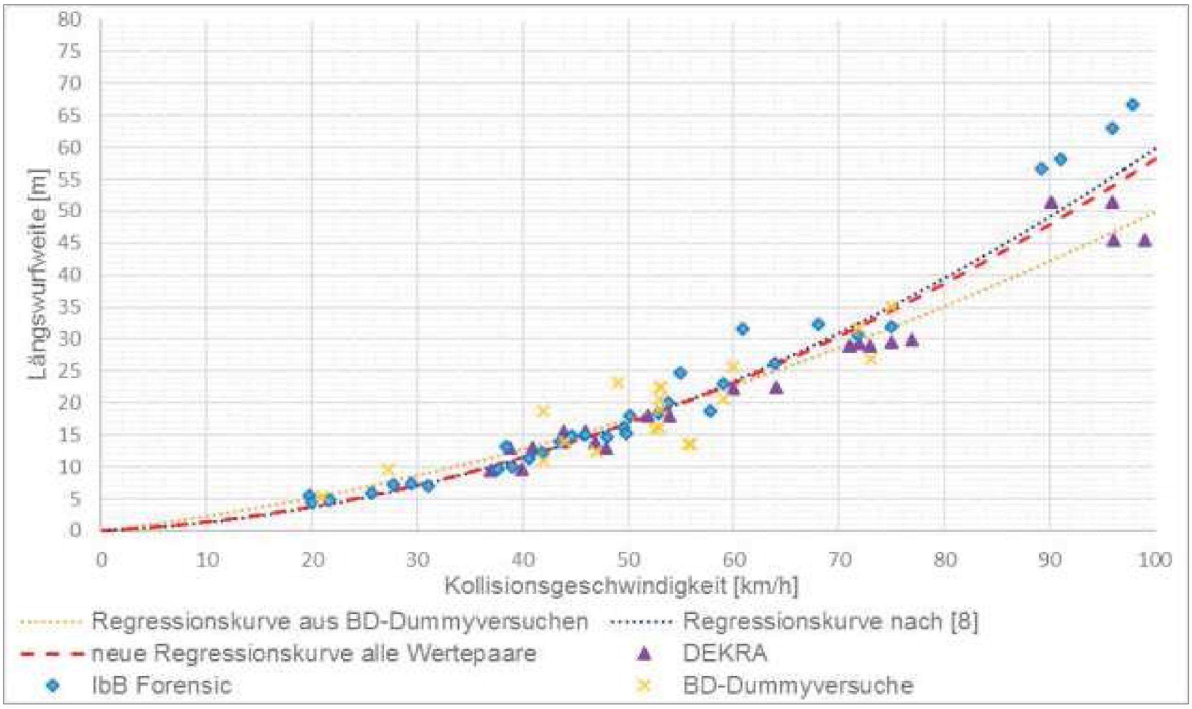

Fig 16: Longitudinal throw distances from real accidents, crash tests with various dummy types and the BD-Dummy with new regression curves according to [13] and [14].

Längswurfweite – longitudinal throw distance, Kollisionsgeschwindigkeit – collision speed, Regressionskurve aus BD-Dummyversuchen – regression curve from ATD crash tests, Regressionskurve nach [8] – regression curve acc. to [8], neue Regressionskurve alle Wertpaare – new regression curve, all value pairs, BD-Dummyversuche – ATD tests