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Abstract:	In traffic accidents, the differentiation of run-over and other injuries is crucial because questions about the origin of fatal injuries often arise. It is sometimes difficult for forensic pathologists to answer them due to the superimposition of injuries or competing, potentially fatal findings. Therefore, using morphometric three-dimensional (3D) reconstructions offers new perspectives based on an interdisciplinary evaluation of all findings and traces. The morphometric 3D reconstruction includes the allocation of patterned injuries or transferred material, the determination of the origin of injuries as well as the reconstruction of the incident. The generated 3D models of persons, clothes, vehicles, incident sites and relevant objects resulting from forensic imaging, photogrammetry, 3D structured-light and laser scanning are included, as are all detected traces and damages. Three case studies are presented to illustrate the possibilities and results of morphometric 3D reconstruction. Run-over accidents have received less attention than the topic of pedestrian, bicycle and motorbike accident analysis for which there is a large body of literature. Our goal is to add to the understanding of run-over accidents using morphometric reconstruction in order to improve their analysis in the future. The possibilities of morphometric reconstructions by means of 3D techniques in run-over accidents are wide-ranging and can provide new, unexpected and significant insights.

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Highlights:

- Incident sites and associated evidenciary findings are documented by means of 3D techniques
- Photogrammetry, optical surface and terrestrial laser scanning as well as CT are used
- 3D reconstruction demonstrates run over accidents even in the absence of clear skeletal trauma
- Morphometric reconstruction is a valuable tool for interdisciplinary analysis of traffic accidents

Abstract

In traffic accidents, the differentiation of run-over and other injuries is crucial because questions about the origin of fatal injuries often arise. It is sometimes difficult for forensic pathologists to answer them due to the superimposition of injuries or competing, potentially fatal findings. Therefore, using morphometric three-dimensional (3D) reconstructions offers new perspectives based on an interdisciplinary evaluation of all findings and traces.

The morphometric 3D reconstruction includes the allocation of patterned injuries or transferred material, the determination of the origin of injuries as well as the reconstruction of the incident. The generated 3D models of persons, clothes, vehicles, incident sites and relevant objects resulting from forensic imaging, photogrammetry, 3D structured-light and laser scanning are included, as are all detected traces and damages. Three case studies are presented to illustrate the possibilities and results of morphometric 3D reconstruction.

Run-over accidents have received less attention than the topic of pedestrian, bicycle and motorbike accident analysis for which there is a large body of literature. Our goal is to add to the understanding of run-over accidents using morphometric reconstruction in order to improve their analysis in the future.

The possibilities of morphometric reconstructions by means of 3D techniques in run-over accidents are wide-ranging and can provide new, unexpected and significant insights.

Keywords

Forensic sciences, 3D documentation, 3D reconstruction, run-over accident, surface scanning

1. Introduction

The reconstruction of traffic accidents can be a complex process. The traces at the incident site, the traces and deformations of the vehicles as well as the injuries of the involved persons and the traces on their clothes have to be appraised. This requires close cooperation of the individual disciplines such as police, legal medicine and accident analysis. In a traditional evaluation of traffic accidents, the involved specialists can gain knowledge of the results of the other disciplines through meetings and reading the final reports. However, different examination methods hamper a joint case evaluation. Using morphometric reconstruction with real-data based true to colour and scale 3D models of the body, vehicle and accident site, a digital joint case evaluation is possible. The 3D reconstruction methods are often used for pedestrian accidents or accidents with bicycles or motorbikes [1]. This field is well published with regard to reconstruction, speed calculation, crash analysis and simulation. However, very few publications deal with run-over accidents in recent years [2-4]. Our goal is to gain more insights into run-over accidents using morphometric reconstruction to improve their analysis in the future. In traffic accidents with run overs[1] [5] the differentiation of run-over injuries and injuries that occurred otherwise is crucial. Typical questions that arise in this context pertain to the event that caused the fatal injuries and which vehicles were involved in which way [6-9]. Answering these questions can be a great challenge for the forensic pathologist due to the superimposition of injuries and / or competing findings that could have led to death [10]. In such cases, the joint evaluation is of even higher importance. The morphometric 3D reconstruction [11, 12] is based on the 3D documentation of the incident site [13, 14], the involved cars and objects [15, 16] and the deceased and / or injured [17-23]. Hence, it is a unique interdisciplinary approach for analysis and assessment.

In 2000 Thali et al. [24] matched patterned skin lesions to tyre profiles in run-over cases. To the best of the authors' knowledge, this research article is the first to present a complete morphometric 3D reconstruction of hit-and-run-over or run-over accidents.

In this paper, three different real case studies are used to illustrate the method and the procedure of morphometric 3D reconstruction in cases of run-over accidents.

[1] All run-over accidents presented in this paper are accidents where at least one wheel went over a part of the body. In literature this type of run over is sometimes also called roll over.

2. Material and methods

Case 1

A man was hit by a wheel loader while crossing the street and subsequently run over. The man died on the scene due to his severe injuries. Numerous witness testimonies were available but they were contradictory. Therefore, basic questions, such as the direction the man had come from, could not be answered.

Besides identifying the cause of death, the goal was to determine how the man was hit by the wheel loader and his direction of movement. When the police arrived at the scene, the fork arms of the wheel loader were lowered. For an assessment of its driver's range of vision at the time of the incident, it was necessary to reconstruct the position of the fork arms.

Case 2

A man was run over on a side street and died at the incident site. There had been a possible previous dispute with the driver of the transporter. It was unclear if the man was intentionally hit by the transporter in the context of a potential homicide and then run over, or if it was an accident.

Case 3

A man fell from a bridge onto a highway and was then run over by two different vehicles. It was assumed to be a suicide. Both vehicles dragged the man along for a few meters. The man died at the incident site. His severe injuries included a blunt craniocerebral trauma with damage of the anterior cervical spine at the base of the skull including brainstem rupture, a massive blunt chest and abdominal trauma as well as an extremity trauma. In order to clarify how the man was run over and what caused the injuries, a morphometric 3D reconstruction was carried out.

The morphometric 3D reconstruction was based on the 3D data of the incident site, the involved cars, objects and clothes of the victims as well as their body surface and internal findings.

The documentation of the incident site was carried out by the police using photogrammetry and terrestrial laser scanning.

In order to generate precise 3D models of the body surface and clothes as well as the involved cars and objects, a TRITOP/ATOS III system (GOM, Braunschweig, Deutschland) was used. This reliable system delivers high resolution and precise 3D surface models of objects in which even small surface structures are visible [25].

Post mortem computed tomography (PMCT) and magnetic resonance imaging (PMMRI) as well as an autopsy were performed for the documentation of the internal findings of the deceased [26-28]. For a better fusion of the surface scan data onto the PMCT data, the surface scan was done on the CT table. Adhesive radiographic markers were used for the registration of the radiological with surface scan data or photos [29].

The OsiriX (Pixmeo SARL, Bernex, Switzerland) software was used for the segmentation of the CT data for generating the 3D models of the skeleton including the individual fractures and the body surface. OsiriX uses the threshold value method to segment 2D medical slice images in a 3D image sequence [30]. The high-resolution true-to-colour and true-to-scale 3D surface models were merged with 3D models derived from PMCT data. Subsequently, the 3D models of the external and internal findings of the deceased were repositioned and visualized using the 3D modelling, animation, and rendering software 3ds Max (Autodesk, San Rafael, USA). For the reconstruction of different body positions an anatomically correct moving computer body model, which was adapted to the actual stature of the deceased, was created.

The 3D models of the injuries and deformations were compared and analysed with respect to their position relative to each other, dimension and shape with the 3ds Max software. The 3D models of the incident site were also used for the evaluation.

Medico-legal, trace-related and forensic findings were included in the scale-based, geometric comparison.

3. Results

Case 1

Thanks to morphometric 3D reconstruction an allocation of the documented findings and traces to the primary hit, to the fall itself and to the run over was possible. The contused wound on the left side of the deceased's forehead could be assigned to an impact of the left side of the fork carrier's top edge via its dimension and shape (Fig. 1a). Moreover, the shaped skin abrasion at the inner side of the left lower leg matched with the fork arm in terms of size and shape (Fig. 1b). These injuries indicate a hit from the man's right side while crossing the street from left to right from the driver's perspective. Furthermore, the height of the fork carrier at the time of collision could be reconstructed based on the location of the injuries caused by the impact (Fig. 2a).

As a consequence of this first impact the deceased fell backwards on his occiput which resulted in a burst fracture system and the contusion respectively hematoma at the back of his head. Furthermore, the reconstruction showed that the deceased was lying on his back when he was rolled over by the left front wheel of the wheel loader (Fig. 2b), which caused the trauma of the trunk.

Case 2

No finding of the victim, the clothes or on the vehicle indicated a contact of the victim with the front of the transporter. The morphometric analysis of the wipe marks on the sliding door showed that they were consistent with fingers of the left hand pointing with the fingertips to the rear end of the vehicle. This is consistent with a transporter driving forward while the man was trying to hold its sliding door (Fig. 3a). Subsequently the man fell on the back of his head. The outcome of this was a burst fracture system at the right side of the occipital protuberance and a contusion above it.

In further sequence of events the man got drawn under the car and was rolled over by the right rear wheel in the direction of the longitudinal axis of his body while lying supine on the ground (Fig. 3b). It was possible to assign the degloving (décollement) [31] of the right lower leg, a haemorrhage into the tissue of the small pelvis, multiple right rib fractures, the patterned injury in the face and the hinge fracture of the skull to the run over (Fig. 4).

The clothes of the deceased were also integrated into the 3D reconstruction. The damages of the trousers, the belt and the right shoe could be assigned to this run over.

The morphometric comparison of the patterned injury, the haemorrhage into the skin on the left side of the deceased's face, with the tyre profile of the transporter revealed a high accordance in number and dimensions and confirmed the run over by this particular transporter (Fig. 4c and 4d).

Case 3

The position of the knocked out teeth on the road, the abrasion in the face and the contused wound on the chin indicate that the man most likely hit the ground with the left side of the head first after the fall from the bridge. The first run over was caused by a transporter (Fig. 5). The patterned abrasions on the inner side of the left thigh match in shape and size to the tyre profile of the right wheels (Fig. 6a). The underlying fracture of the femur and the degloving injury support the assumption of a run over. While the left leg was rolled over by the rear wheel and fixated on the street, the right leg was likely clamped between the cross brace of the rear axle and the underside. This position of the right leg (Fig. 6b) is indicated by the patterned abrasion on the right thigh with the skin rupture likely originating from the contact with the pickup point of the bump stop (Fig. 7a) and the shoe print on the cross brace (Fig. 7b). The massive thorax trauma with a degloving injury on the right and left side of the thorax could be explained by the roll over by the two left wheels of the second car. The traces and injuries lead to the assumption that the deceased was rolled over in prone position by the left front wheel and then rolled over again in supine position by the left rear wheel. The patterned traces of transferred material on the right flank (Fig. 8a) match the tyre profile of the car, and the distance between the skin abrasions under the traces (Fig. 8b) is consistent with the distance between tyre tread gaps and tyre width. The tissue and blood traces on the rear cross strut and the spare wheel are explainable by a contact with the massive open rupture of the right thigh (Fig. 8c).

4. Discussion

The morphometric reconstruction of run-over accidents can be of great importance in finding out which vehicle ran over a person and in which position the person was run over, and to identify what happened before the run over.

The first case illustrates that very clearly. Numerous people were apparently present at the time of the accident and had supposedly even seen it. The subsequent questioning by the police showed that the witness reports were strongly contradictory so that this source of evidence could not be used. The 3D documentation and reconstruction provided an impressive result that was admitted in court. The results indicated that the pedestrian wanted to cross the street from the left to the right side from the driver's perspective when he was hit by the fork arm and fork carrier of the wheel loader. Furthermore, based on the determined height of the fork carrier at the time of collision it was possible to illustrate how the driver's range of vision was substantially limited by the fork carrier.

The second case was solved thanks to 3D reconstruction and the possibility of assigning findings. The first suspicion of a homicide was refuted. Testimonies and hypotheses could be checked and eliminated or confirmed. The lack of severe injuries that would usually be expected in cases of run-over accidents could be conclusively explained by the constellation (vehicle-victim-position) and the low speed of the vehicle during the run over. Despite missing trace DNA on the wheels as a result of the onward journey and the rain it could be verified that the tyre of this particular transporter matched the injury of the victim. Together with the positive DNA hit from the wipe marks on the sliding door and the reconstructed possible course of the accident, there were no more clues for a homicide or other involved parties.

In the third case the initial situation was more complex due to massive destruction of the body from being run over twice with high velocity. Despite these difficulties, an allocation of the findings by 3D reconstruction was possible. It was shown that even with overlapping injuries an assignment of the injuries to the different phases of the event was possible.

The cases were chosen to illustrate and discuss the different advantages and novelties the morphometric reconstruction can offer in cases ranging from a hit-and-run case with low speed to a high-speed accident with a complete destruction of a body to a possible crime.

In all cases the morphometric 3D reconstruction was performed after the final report by the forensic pathologist and the police had been written and in which questions remained unanswered. Only after the presentation of the results of the morphometric reconstruction the case seemed clear for all parties.

In pedestrian accidents or accidents with bicycles or motorbikes the vehicle normally has visible damage. In many run-over accidents this is not the case because of its low speed. Sometimes swipes or contact material are visible but often it is not clear if they were caused by the accident or not, thus complicating the task of finding out what happened. When the point of contact between the vehicle and the deceased is unknown, the task is to compare the patterned injuries with all possible parts of the vehicle as in case three. In the first case, the patterned injury is on the left side of the forehead. This would normally suggest a contact from the left side. However, the impact to the body had come from the right side and only a part of the forehead had contact with the left side of the fork carrier's top edge. While the other side of the fork carrier's top edge looks similar, the geometric comparison shows that it does not match the injury.

By applying morphometric reconstruction based on all findings and traces it was shown that a person had been run over by a vehicle despite relatively minor skeletal trauma. Traditionally, a run over was inferred from the severity of the skeleton trauma. We have seen many cases in which the internal findings did not suggest a run over that was nevertheless confirmed by the morphometric reconstruction. This is an interesting new topic in the run-over accident analysis, which needs further scientific research.

The cases presented here show that 3D reconstruction can be of enormous importance for jurisdiction especially if legal questions remain open after sighting all case documents [32].

Nowadays, at the authors' host institute the body surface documentation of deceased and living persons and all injuries is performed with the hand-held scanner Go!Scan 50 (Creaform/Ametek, Québec, Canada) and in addition with photogrammetric pictures using a DSLR camera (Nikon Z6, Nikon, Inc., Tokyo, Japan). For each side of the body, the documentation takes approx. 5 minutes for the 3D scanning and approx. 7 minutes for the photogrammetric pictures [25]. The AGISOFT Metashape software (Agisoft, St. Petersburg, Russia) is used for the evaluation of the photogrammetric pictures. Compared to the surface documentation with the TRITOP/ATOS III system, the time of data acquisition is reduced considerably. As a result, 3D documentation is performed in more and more cases to allow for a morphometric comparison should reconstructive questions arise later. With the rapid development of hard- and software in the field of 3D technology, the equipment is becoming easier and faster to use as well as more affordable [25].

With the increase of quantity and quality of the data and the resulting interdisciplinary morphometric 3D reconstructions, statements about the incident can be more specific and the range of tolerance is significantly restricted.

During investigations of traffic accidents in the course of a lawsuit, numerous questions may arise. In the example of a pedestrian collision this could be the vitality or the walking direction. For a collision with a motorbike or a bicycle this can be the configuration of collision, and when there were multiple collisions which of them led to the fatal injuries. In the case of a hit-and-run accident, the question can pertain to the involvement of traffic participants in the accident. Who was driving, based on the injuries of the passengers, can also be a juristic question.

Cases in which answers to these and similar questions cannot be found by means of medical investigations alone sometimes require interdisciplinary collaboration as provided by a 3D documentation and morphometric 3D reconstruction. The further development of measuring methods already allows for a cost-efficient, easy and fast data acquisition that can be done by everyone after a short instruction. Thanks to this a 3D documentation of the external findings can be performed routinely in many cases. In contrast, the morphometric 3D reconstruction utilizing all findings and traces is time consuming and usually only carried out in unclear cases, especially if new relevant hints, evidence and findings are expected.

The results of our geometrical and true scaled comparisons and reconstructions are based on an excellent cooperation of forensic medicine, police and other experts. The body surface documentation and the 3D reconstructions of accidents and events has become a significant field of work in our institute with great potential for further development especially in cases of run-over accidents.

5. Conclusion

The morphometric 3D reconstruction allows for an interdisciplinary approach and new perspectives in traffic accident analysis. The morphometric reconstruction is an indispensable method in the evaluation of hit-and-run-over or run-over traffic accidents.

Legends

Fig. 1 Case 1: Morphometrical matches.

a) Contused wound on the left side of the deceased's forehead (red arrows), which matches with a part of the wheel loader's fork carrier (red circle). Reconstructed 3D view for this match.

b) Part of the wheel loader's fork arms (red box) which matches with the skin abrasion on the left lower leg of the deceased (red arrows). Reconstructed 3D view for this match.

Fig. 2 Case 1: Reconstruction results for the position of the fork carrier of the wheel loader and the run over

a) Reconstructed position of the wheel loader's fork carrier during the accident.

b) Reconstructed run over of the victim in supine position on the ground by the wheel loader's front left wheel shown with the 3D documented skin surface and tyre as well as with the PMCT documented skeleton of the deceased.

Fig. 3

a) Case 2: 3D reconstruction of the accident with the man standing at the right side door of the transporter moving forward (white arrow)

b) Case 2: 3D reconstruction of the accident with the man lying under the transporter before the run over

Fig. 4 Case 2: Reconstructed roll over

a) Rib fractures on the ventral right side of the thorax seen in the PMCT (yellow arrows)

b) Reconstructed roll over of the deceased (depicted with head by skin surface documentation, upper body by PMCT and extremities by fitted digital body model) in body's longitudinal axis with marked roll-over direction of the tyre (white arrow)

c) 3D model of the patterned injury on the head's left side

d) Texture mapped 3D skin surface of the head's left side with the patterned injury and superimposed matched tyre of the transporter with direction of the run over (white arrow)

Fig. 5 Case 3: 3D reconstruction of the first run over with a transporter

a) View from the right side

b) View from the top through the underbody

c) View from the front

Fig. 6 Case 3: 3D reconstruction of the first run over showing the matched injuries

a) Match between patterned injuries on the inner left thigh and both right tyres of the transporter (match with right front tyre (green arrows), match with right back tyre (blue arrows)).

b) The bone fractures of the right thigh and lower limb may have occurred during contact with the cross brace (green arrows).

The patterned injury with abrasion and lesion on the right thigh matches the size of the missing right bump stop (blue arrow) (see fig. 9 a).

Transferred black material on the right shoe and white abrasion on the cross brace of the rear axle (see fig 9 b).

c) Possible position of how the right limb was clamped between cross brace of the rear axle and underside (view from the bottom).

Fig. 7 Case 3: Geometrical comparisons between injuries and parts of the underbody of the transporter / traces on the underbody of the transporter

a) Geometrical comparison of the missing bump stop with the patterned injury on the right thigh. The diameter of the abrasion matches the diameter of the bump stop (green markers).

b) Geometrical comparison of the shoe sole print and white abrasion on the cross brace of the rear axle with the deceased's right shoe. The shoe print (green arrows) and the white abrasion (blue arrows) match the right side of the right shoe.

Fig. 8 Case 3: Matched traces and patterned injuries of the second run over

a) Transferred material on the right flank of the deceased matches the tyre tread of the car.

b) The skin abrasion matches the tyre tread and the width of the tyre in shape and size.

c) Possible reconstructed position of the deceased during the run over of the car’s left rear wheel (view from the top through the underbody). Picture of the transferred tissue and blood on the spare wheel.

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Abstract

In traffic accidents, the differentiation of run-over and other injuries is crucial because questions about the origin of fatal injuries often arise. It is sometimes difficult for forensic pathologists to answer them due to the superimposition of injuries or competing, potentially fatal findings. Therefore, using morphometric three-dimensional (3D) reconstructions offers new perspectives based on an interdisciplinary evaluation of all findings and traces.

The morphometric 3D reconstruction includes the allocation of patterned injuries or transferred material, the determination of the origin of injuries as well as the reconstruction of the incident. The generated 3D models of persons, clothes, vehicles, incident sites and relevant objects resulting from forensic imaging, photogrammetry, 3D structured-light and laser scanning are included, as are all detected traces and damages. Three case studies are presented to illustrate the possibilities and results of morphometric 3D reconstruction.

Run-over accidents have received less attention than the topic of pedestrian, bicycle and motorbike accident analysis for which there is a large body of literature. Our goal is to add to the understanding of run-over accidents using morphometric reconstruction in order to improve their analysis in the future.

The possibilities of morphometric reconstructions by means of 3D techniques in run-over accidents are wide-ranging and can provide new, unexpected and significant insights.

Keywords

Forensic sciences, 3D documentation, 3D reconstruction, run-over accident, surface scanning

1. Introduction

The reconstruction of traffic accidents can be a complex process. The traces at the incident site, the traces and deformations of the vehicles as well as the injuries of the involved persons and the traces on their clothes have to be appraised. This requires close cooperation of the individual disciplines such as police, legal medicine and accident analysis. In a traditional evaluation of traffic accidents, the involved specialists can gain knowledge of the results of the other disciplines through meetings and reading the final reports. However, different examination methods hamper a joint case evaluation. Using morphometric reconstruction with real-data based true to colour and scale 3D models of the body, vehicle and accident site, a digital joint case evaluation is possible. The 3D reconstruction methods are often used for pedestrian accidents or accidents with bicycles or motorbikes [1]. This field is well published with regard to reconstruction, speed calculation, crash analysis and simulation. However, very few publications deal with run-over accidents in recent years [2-4]. Our goal is to gain more insights into run-over accidents using morphometric reconstruction to improve their analysis in the future. In traffic accidents with run overs[1] [5] the differentiation of run-over injuries and injuries that occurred otherwise is crucial. Typical questions that arise in this context pertain to the event that caused the fatal injuries and which vehicles were involved in which way [6-9]. Answering these questions can be a great challenge for the forensic pathologist due to the superimposition of injuries and / or competing findings that could have led to death [10]. In such cases, the joint evaluation is of even higher importance. The morphometric 3D reconstruction [11, 12] is based on the 3D documentation of the incident site [13, 14], the involved cars and objects [15, 16] and the deceased and / or injured [17-23]. Hence, it is a unique interdisciplinary approach for analysis and assessment.

In 2000 Thali et al. [24] matched patterned skin lesions to tyre profiles in run-over cases. To the best of the authors' knowledge, this research article is the first to present a complete morphometric 3D reconstruction of hit-and-run-over or run-over accidents.

In this paper, three different real case studies are used to illustrate the method and the procedure of morphometric 3D reconstruction in cases of run-over accidents.

[1] All run-over accidents presented in this paper are accidents where at least one wheel went over a part of the body. In literature this type of run over is sometimes also called roll over.

2. Material and methods

Case 1

A man was hit by a wheel loader while crossing the street and subsequently run over. The man died on the scene due to his severe injuries. Numerous witness testimonies were available but they were contradictory. Therefore, basic questions, such as the direction the man had come from, could not be answered.

Besides identifying the cause of death, the goal was to determine how the man was hit by the wheel loader and his direction of movement. When the police arrived at the scene, the fork arms of the wheel loader were lowered. For an assessment of its driver's range of vision at the time of the incident, it was necessary to reconstruct the position of the fork arms.

Case 2

A man was run over on a side street and died at the incident site. There had been a possible previous dispute with the driver of the transporter. It was unclear if the man was intentionally hit by the transporter in the context of a potential homicide and then run over, or if it was an accident.

Case 3

A man fell from a bridge onto a highway and was then run over by two different vehicles. It was assumed to be a suicide. Both vehicles dragged the man along for a few meters. The man died at the incident site. His severe injuries included a blunt craniocerebral trauma with damage of the anterior cervical spine at the base of the skull including brainstem rupture, a massive blunt chest and abdominal trauma as well as an extremity trauma. In order to clarify how the man was run over and what caused the injuries, a morphometric 3D reconstruction was carried out.

The morphometric 3D reconstruction was based on the 3D data of the incident site, the involved cars, objects and clothes of the victims as well as their body surface and internal findings.

The documentation of the incident site was carried out by the police using photogrammetry and terrestrial laser scanning.

In order to generate precise 3D models of the body surface and clothes as well as the involved cars and objects, a TRITOP/ATOS III system (GOM, Braunschweig, Deutschland) was used. This reliable system delivers high resolution and precise 3D surface models of objects in which even small surface structures are visible [25].

Post mortem computed tomography (PMCT) and magnetic resonance imaging (PMMRI) as well as an autopsy were performed for the documentation of the internal findings of the deceased [26-28]. For a better fusion of the surface scan data onto the PMCT data, the surface scan was done on the CT table. Adhesive radiographic markers were used for the registration of the radiological with surface scan data or photos [29].

The OsiriX (Pixmeo SARL, Bernex, Switzerland) software was used for the segmentation of the CT data for generating the 3D models of the skeleton including the individual fractures and the body surface. OsiriX uses the threshold value method to segment 2D medical slice images in a 3D image sequence [30]. The high-resolution true-to-colour and true-to-scale 3D surface models were merged with 3D models derived from PMCT data. Subsequently, the 3D models of the external and internal findings of the deceased were repositioned and visualized using the 3D modelling, animation, and rendering software 3ds Max (Autodesk, San Rafael, USA). For the reconstruction of different body positions an anatomically correct moving computer body model, which was adapted to the actual stature of the deceased, was created.

The 3D models of the injuries and deformations were compared and analysed with respect to their position relative to each other, dimension and shape with the 3ds Max software. The 3D models of the incident site were also used for the evaluation.

Medico-legal, trace-related and forensic findings were included in the scale-based, geometric comparison.

3. Results

Case 1

Thanks to morphometric 3D reconstruction an allocation of the documented findings and traces to the primary hit, to the fall itself and to the run over was possible. The contused wound on the left side of the deceased’s forehead could be assigned to an impact of the left side of the fork carrier’s top edge via its dimension and shape (Fig. 1a). Moreover, the shaped skin abrasion at the inner side of the left lower leg matched with the fork arm in terms of size and shape (Fig. 1b). These injuries indicate a hit from the man’s right side while crossing the street from left to right from the driver's perspective. Furthermore, the height of the fork carrier at the time of collision could be reconstructed based on the location of the injuries caused by the impact (Fig. 2a).

As a consequence of this first impact the deceased fell backwards on his occiput which resulted in a burst fracture system and the contusion respectively hematoma at the back of his head. Furthermore, the reconstruction showed that the deceased was lying on his back when he was rolled over by the left front wheel of the wheel loader (Fig. 2b), which caused the trauma of the trunk.

Case 2

No finding of the victim, the clothes or on the vehicle indicated a contact of the victim with the front of the transporter. The morphometric analysis of the wipe marks on the sliding door showed that they were consistent with fingers of the left hand pointing with the fingertips to the rear end of the vehicle. This is consistent with a transporter driving forward while the man was trying to hold its sliding door (Fig. 3a). Subsequently the man fell on the back of his head. The outcome of this was a burst fracture system at the right side of the occipital protuberance and a contusion above it.

In further sequence of events the man got drawn under the car and was rolled over by the right rear wheel in the direction of the longitudinal axis of his body while lying supine on the ground (Fig. 3b). It was possible to assign the degloving (décollement) [31] of the right lower leg, a haemorrhage into the tissue of the small pelvis, multiple right rib fractures, the patterned injury in the face and the hinge fracture of the skull to the run over (Fig. 4).

The clothes of the deceased were also integrated into the 3D reconstruction. The damages of the trousers, the belt and the right shoe could be assigned to this run over.

The morphometric comparison of the patterned injury, the haemorrhage into the skin on the left side of the deceased’s face, with the tyre profile of the transporter revealed a high accordance in number and dimensions and confirmed the run over by this particular transporter (Fig. 4c and 4d).

Case 3

The position of the knocked out teeth on the road, the abrasion in the face and the contused wound on the chin indicate that the man most likely hit the ground with the left side of the head first after the fall from the bridge. The first run over was caused by a transporter (Fig. 5). The patterned abrasions on the inner side of the left thigh match in shape and size to the tyre profile of the right wheels (Fig. 6a). The underlying fracture of the femur and the degloving injury support the assumption of a run over. While the left leg was rolled over by the rear wheel and fixated on the street, the right leg was likely clamped between the cross brace of the rear axle and the underside. This position of the right leg (Fig. 6b) is indicated by the patterned abrasion on the right thigh with the skin rupture likely originating from the contact with the pickup point of the bump stop (Fig. 7a) and the shoe print on the cross brace (Fig. 7b). The massive thorax trauma with a degloving injury on the right and left side of the thorax could be explained by the roll over by the two left wheels of the second car. The traces and injuries lead to the assumption that the deceased was rolled over in prone position by the left front wheel and then rolled over again in supine position by the left rear wheel. The patterned traces of transferred material on the right flank (Fig. 8a) match the tyre profile of the car, and the distance between the skin abrasions under the traces (Fig. 8b) is consistent with the distance between tyre tread gaps and tyre width. The tissue and blood traces on the rear cross strut and the spare wheel are explainable by a contact with the massive open rupture of the right thigh (Fig. 8c).

4. Discussion

The morphometric reconstruction of run-over accidents can be of great importance in finding out which vehicle ran over a person and in which position the person was run over, and to identify what happened before the run over.

The first case illustrates that very clearly. Numerous people were apparently present at the time of the accident and had supposedly even seen it. The subsequent questioning by the police showed that the witness reports were strongly contradictory so that this source of evidence could not be used. The 3D documentation and reconstruction provided an impressive result that was admitted in court. The results indicated that the pedestrian wanted to cross the street from the left to the right side from the driver’s perspective when he was hit by the fork arm and fork carrier of the wheel loader. Furthermore, based on the determined height of the fork carrier at the time of collision it was possible to illustrate how the driver's range of vision was substantially limited by the fork carrier.

The second case was solved thanks to 3D reconstruction and the possibility of assigning findings. The first suspicion of a homicide was refuted. Testimonies and hypotheses could be checked and eliminated or confirmed. The lack of severe injuries that would usually be expected in cases of run-over accidents could be conclusively explained by the constellation (vehicle-victim-position) and the low speed of the vehicle during the run over. Despite missing trace DNA on the wheels as a result of the onward journey and the rain it could be verified that the tyre of this particular transporter matched the injury of the victim. Together with the positive DNA hit from the wipe marks on the sliding door and the reconstructed possible course of the accident, there were no more clues for a homicide or other involved parties.

In the third case the initial situation was more complex due to massive destruction of the body from being run over twice with high velocity. Despite these difficulties, an allocation of the findings by 3D reconstruction was possible. It was shown that even with overlapping injuries an assignment of the injuries to the different phases of the event was possible.

The cases were chosen to illustrate and discuss the different advantages and novelties the morphometric reconstruction can offer in cases ranging from a hit-and-run case with low speed to a high-speed accident with a complete destruction of a body to a possible crime.

In all cases the morphometric 3D reconstruction was performed after the final report by the forensic pathologist and the police had been written and in which questions remained unanswered. Only after the presentation of the results of the morphometric reconstruction the case seemed clear for all parties.

In pedestrian accidents or accidents with bicycles or motorbikes the vehicle normally has visible damage. In many run-over accidents this is not the case because of its low speed. Sometimes swipes or contact material are visible but often it is not clear if they were caused by the accident or not, thus complicating the task of finding out what happened. When the point of contact between the vehicle and the deceased is unknown, the task is to compare the patterned injuries with all possible parts of the vehicle as in case three. In the first case, the patterned injury is on the left side of the forehead. This would normally suggest a contact from the left side. However, the impact to the body had come from the right side and only a part of the forehead had contact with the left side of the fork carrier's top edge. While the other side of the fork carrier's top edge looks similar, the geometric comparison shows that it does not match the injury.

By applying morphometric reconstruction based on all findings and traces it was shown that a person had been run over by a vehicle despite relatively minor skeletal trauma. Traditionally, a run over was inferred from the severity of the skeleton trauma. We have seen many cases in which the internal findings did not suggest a run over that was nevertheless confirmed by the morphometric reconstruction. This is an interesting new topic in the run-over accident analysis, which needs further scientific research.

The cases presented here show that 3D reconstruction can be of enormous importance for jurisdiction especially if legal questions remain open after sighting all case documents [32].

Nowadays, at the authors' host institute the body surface documentation of deceased and living persons and all injuries is performed with the hand-held scanner Go!Scan 50 (Creaform/Ametek, Québec, Canada) and in addition with photogrammetric pictures using a DSLR camera (Nikon Z6, Nikon, Inc., Tokyo, Japan). For each side of the body, the documentation takes approx. 5 minutes for the 3D scanning and approx. 7 minutes for the photogrammetric pictures [25]. The AGISOFT Metashape software (Agisoft, St. Petersburg, Russia) is used for the evaluation of the photogrammetric pictures. Compared to the surface documentation with the TRITOP/ATOS III system, the time of data acquisition is reduced considerably. As a result, 3D documentation is performed in more and more cases to allow for a morphometric comparison should reconstructive questions arise later. With the rapid development of hard- and software in the field of 3D technology, the equipment is becoming easier and faster to use as well as more affordable [25].

With the increase of quantity and quality of the data and the resulting interdisciplinary morphometric 3D reconstructions, statements about the incident can be more specific and the range of tolerance is significantly restricted.

During investigations of traffic accidents in the course of a lawsuit, numerous questions may arise. In the example of a pedestrian collision this could be the vitality or the walking direction. For a collision with a motorbike or a bicycle this can be the configuration of collision, and when there were multiple collisions which of them led to the fatal injuries. In the case of a hit-and-run accident, the question can pertain to the involvement of traffic participants in the accident. Who was driving, based on the injuries of the passengers, can also be a juristic question.

Cases in which answers to these and similar questions cannot be found by means of medical investigations alone sometimes require interdisciplinary collaboration as provided by a 3D documentation and morphometric 3D reconstruction. The further development of measuring methods already allows for a cost-efficient, easy and fast data acquisition that can be done by everyone after a short instruction. Thanks to this a 3D documentation of the external findings can be performed routinely in many cases. In contrast, the morphometric 3D reconstruction utilizing all findings and traces is time consuming and usually only carried out in unclear cases, especially if new relevant hints, evidence and findings are expected.

The results of our geometrical and true scaled comparisons and reconstructions are based on an excellent cooperation of forensic medicine, police and other experts. The body surface documentation and the 3D reconstructions of accidents and events has become a significant field of work in our institute with great potential for further development especially in cases of run-over accidents.

5. Conclusion

The morphometric 3D reconstruction allows for an interdisciplinary approach and new perspectives in traffic accident analysis. The morphometric reconstruction is an indispensable method in the evaluation of hit-and-run-over or run-over traffic accidents.

Legends

Fig. 1 Case 1: Morphometrical matches.

a) Contused wound on the left side of the deceased's forehead (red arrows), which matches with a part of the wheel loader's fork carrier (red circle). Reconstructed 3D view for this match.

b) Part of the wheel loader's fork arms (red box) which matches with the skin abrasion on the left lower leg of the deceased (red arrows). Reconstructed 3D view for this match.

Fig. 2 Case 1: Reconstruction results for the position of the fork carrier of the wheel loader and the run over

a) Reconstructed position of the wheel loader's fork carrier during the accident.

b) Reconstructed run over of the victim in supine position on the ground by the wheel loader's front left wheel shown with the 3D documented skin surface and tyre as well as with the PMCT documented skeleton of the deceased.

Fig. 3

a) Case 2: 3D reconstruction of the accident with the man standing at the right side door of the transporter moving forward (white arrow)

b) Case 2: 3D reconstruction of the accident with the man lying under the transporter before the run over

Fig. 4 Case 2: Reconstructed roll over

a) Rib fractures on the ventral right side of the thorax seen in the PMCT (yellow arrows)

b) Reconstructed roll over of the deceased (depicted with head by skin surface documentation, upper body by PMCT and extremities by fitted digital body model) in body's longitudinal axis with marked roll-over direction of the tyre (white arrow)

c) 3D model of the patterned injury on the head's left side

d) Texture mapped 3D skin surface of the head's left side with the patterned injury and superimposed matched tyre of the transporter with direction of the run over (white arrow)

Fig. 5 Case 3: 3D reconstruction of the first run over with a transporter

a) View from the right side

b) View from the top through the underbody

c) View from the front

Fig. 6 Case 3: 3D reconstruction of the first run over showing the matched injuries

a) Match between patterned injuries on the inner left thigh and both right tyres of the transporter (match with right front tyre (green arrows), match with right back tyre (blue arrows)).

b) The bone fractures of the right thigh and lower limb may have occurred during contact with the cross brace (green arrows).

The patterned injury with abrasion and lesion on the right thigh matches the size of the missing right bump stop (blue arrow) (see fig. 9 a).

Transferred black material on the right shoe and white abrasion on the cross brace of the rear axle (see fig 9 b).

c) Possible position of how the right limb was clamped between cross brace of the rear axle and underside (view from the bottom).

Fig. 7 Case 3: Geometrical comparisons between injuries and parts of the underbody of the transporter / traces on the underbody of the transporter

a) Geometrical comparison of the missing bump stop with the patterned injury on the right thigh. The diameter of the abrasion matches the diameter of the bump stop (green markers).

b) Geometrical comparison of the shoe sole print and white abrasion on the cross brace of the rear axle with the deceased's right shoe. The shoe print (green arrows) and the white abrasion (blue arrows) match the right side of the right shoe.

Fig. 8 Case 3: Matched traces and patterned injuries of the second run over

a) Transferred material on the right flank of the deceased matches the tyre tread of the car.

b) The skin abrasion matches the tyre tread and the width of the tyre in shape and size.

c) Possible reconstructed position of the deceased during the run over of the car’s left rear wheel (view from the top through the underbody). Picture of the transferred tissue and blood on the spare wheel.

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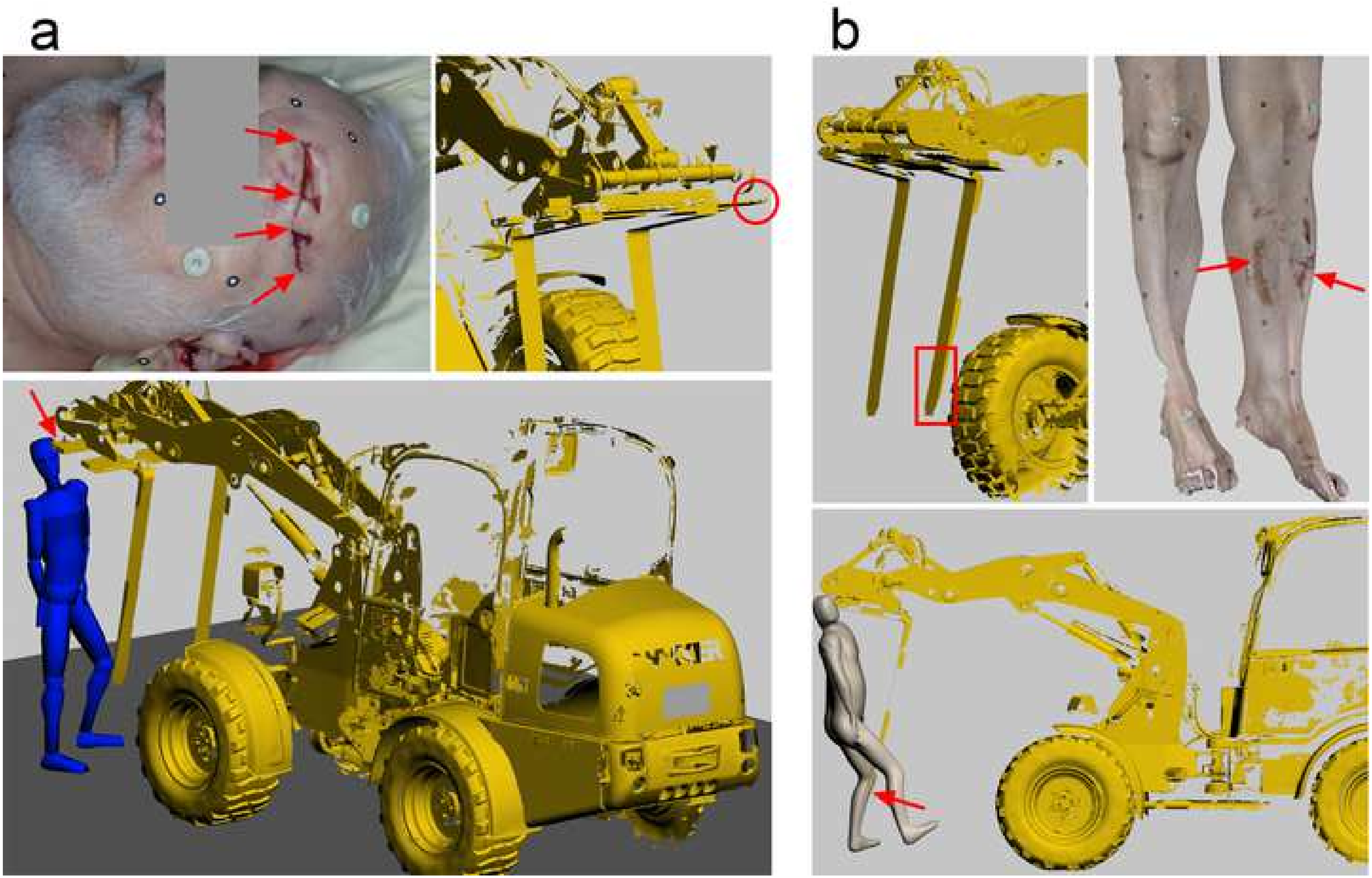
Figure 1



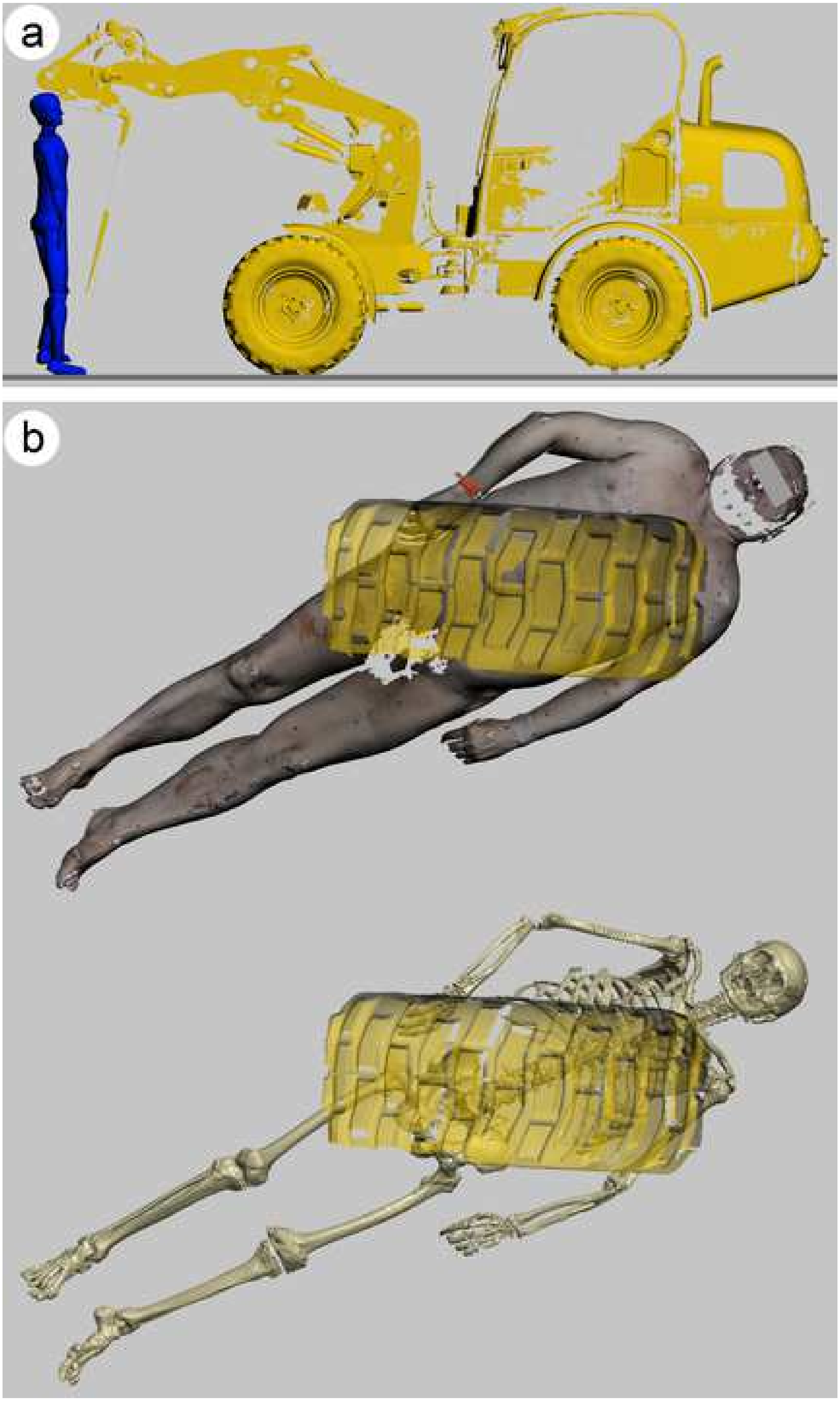

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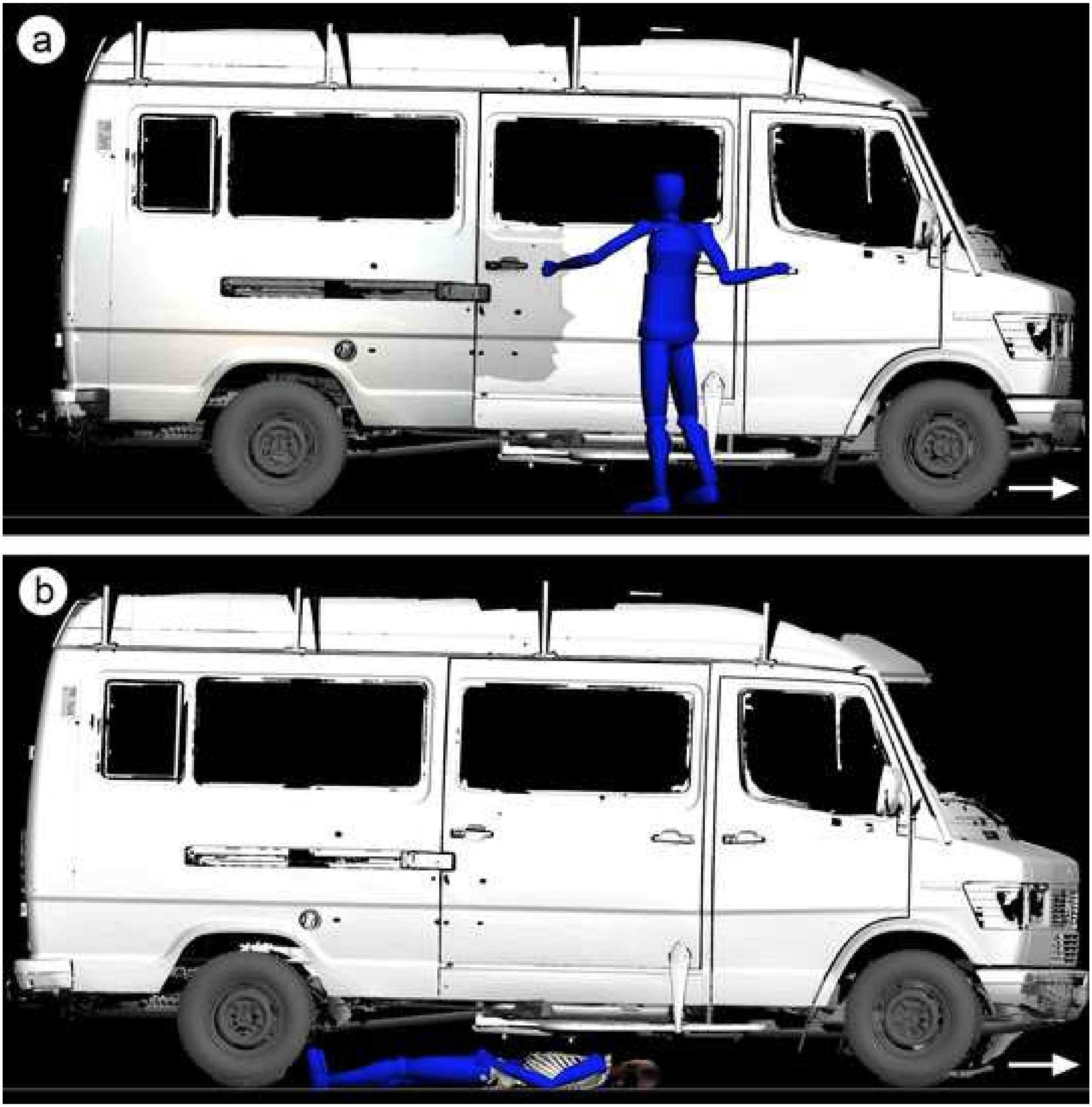
Figure 3



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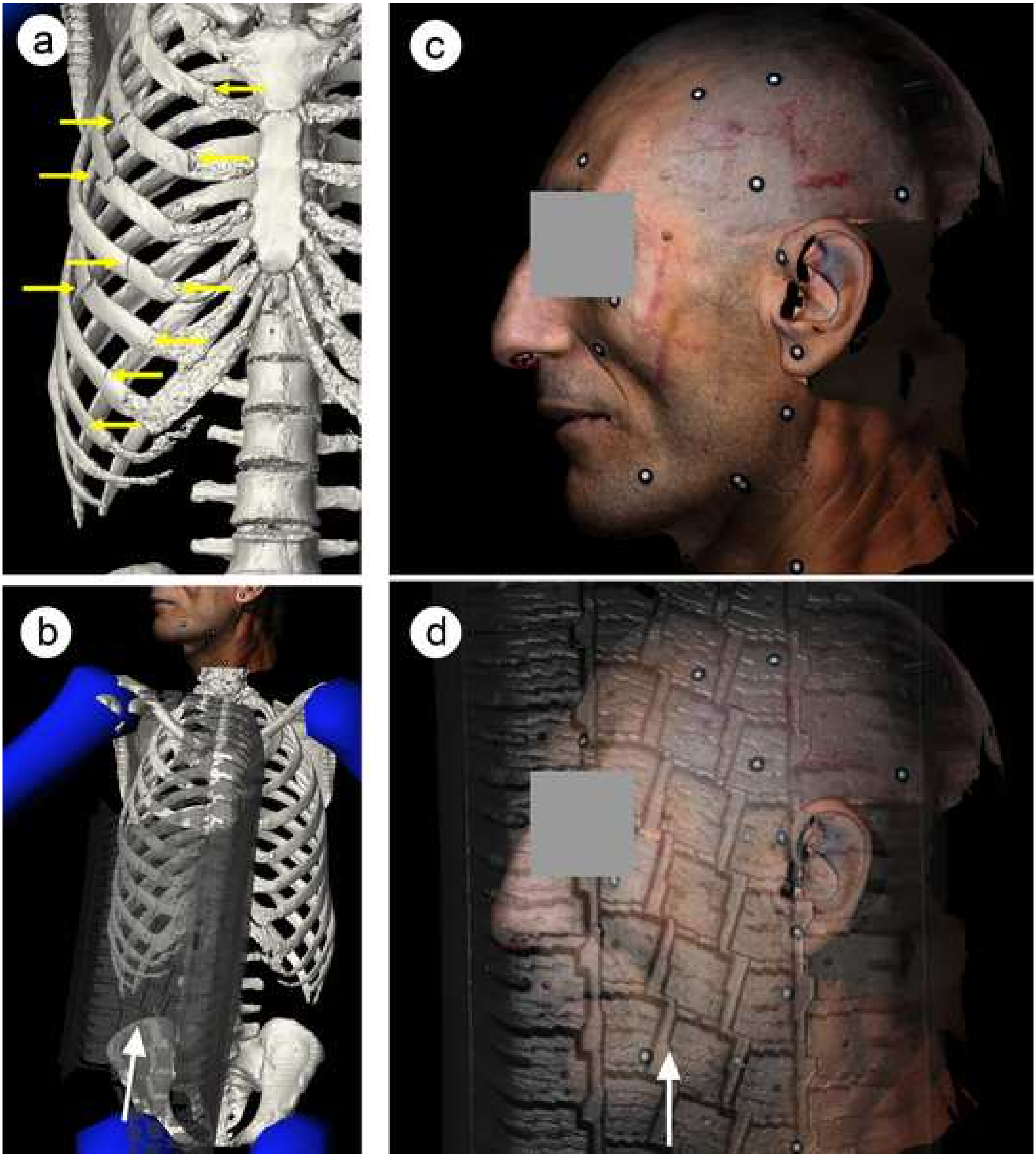

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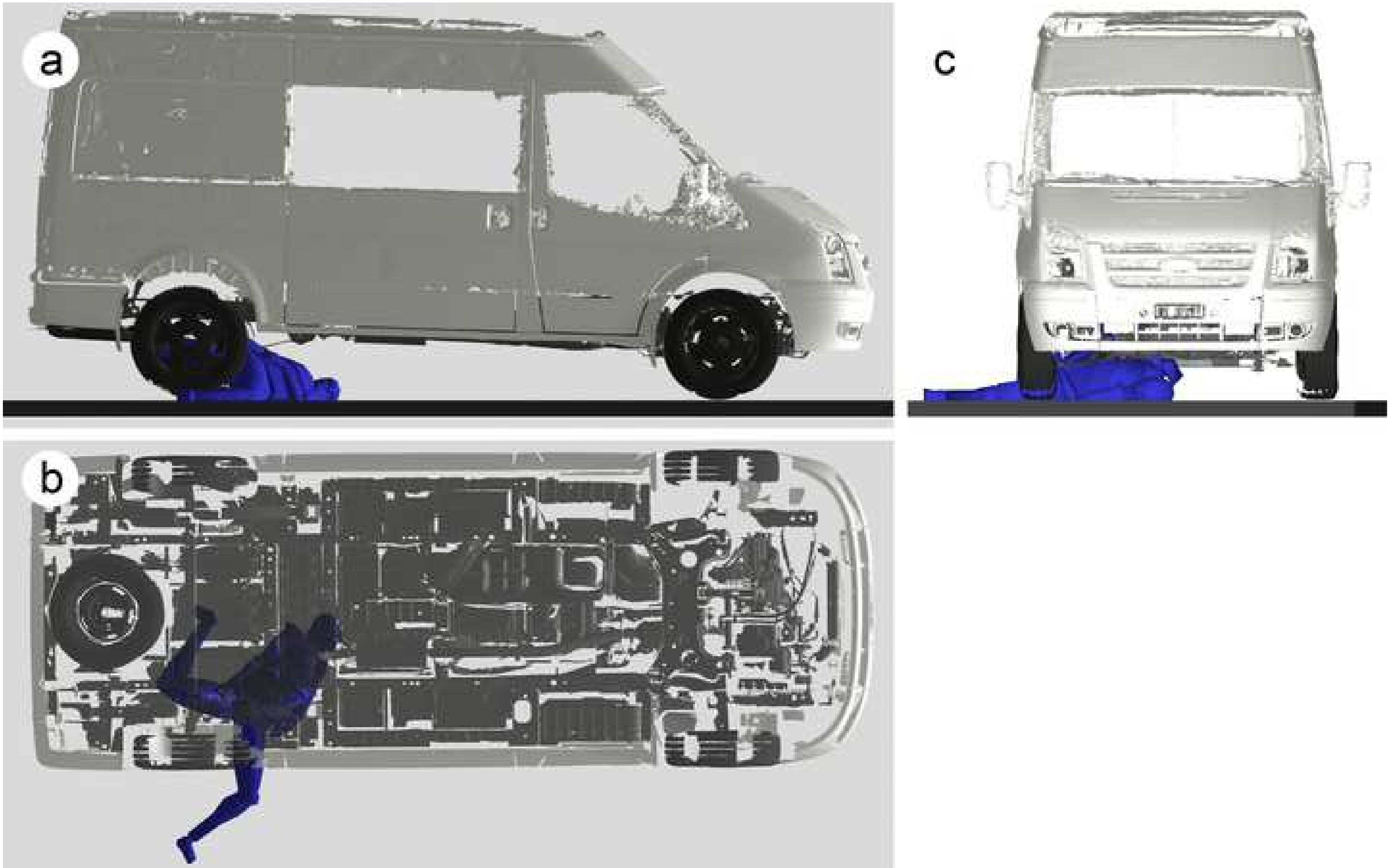

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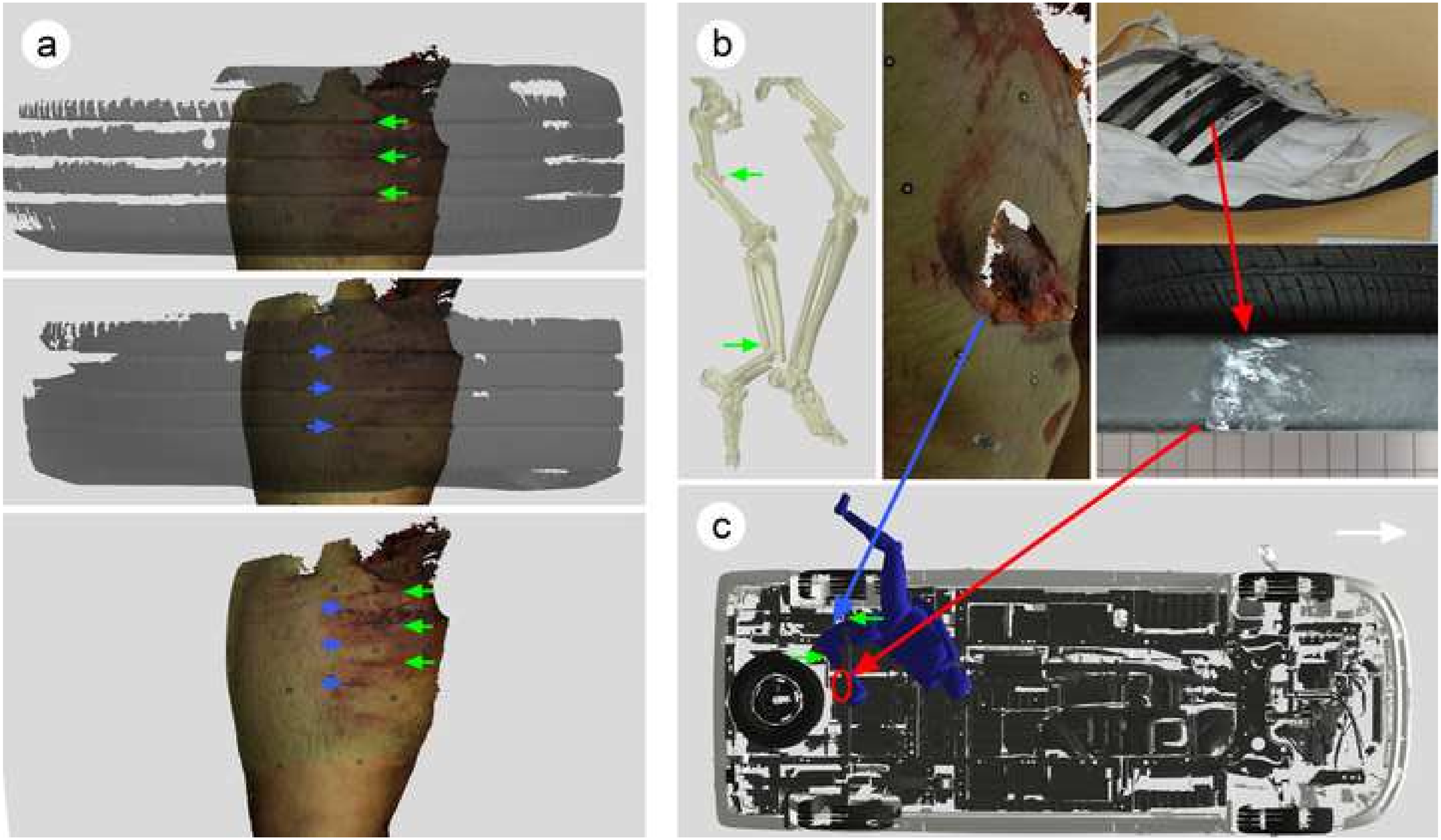

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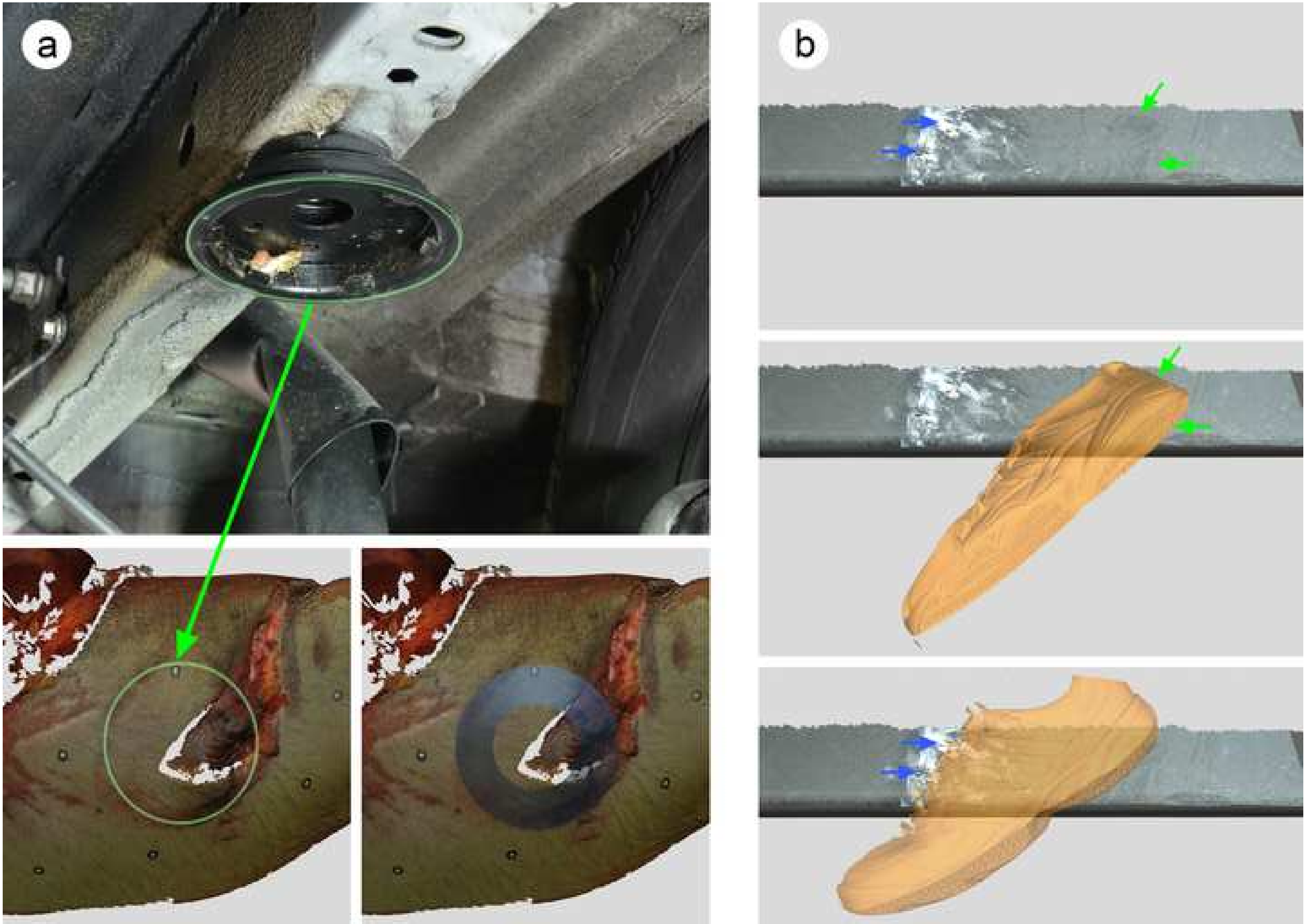

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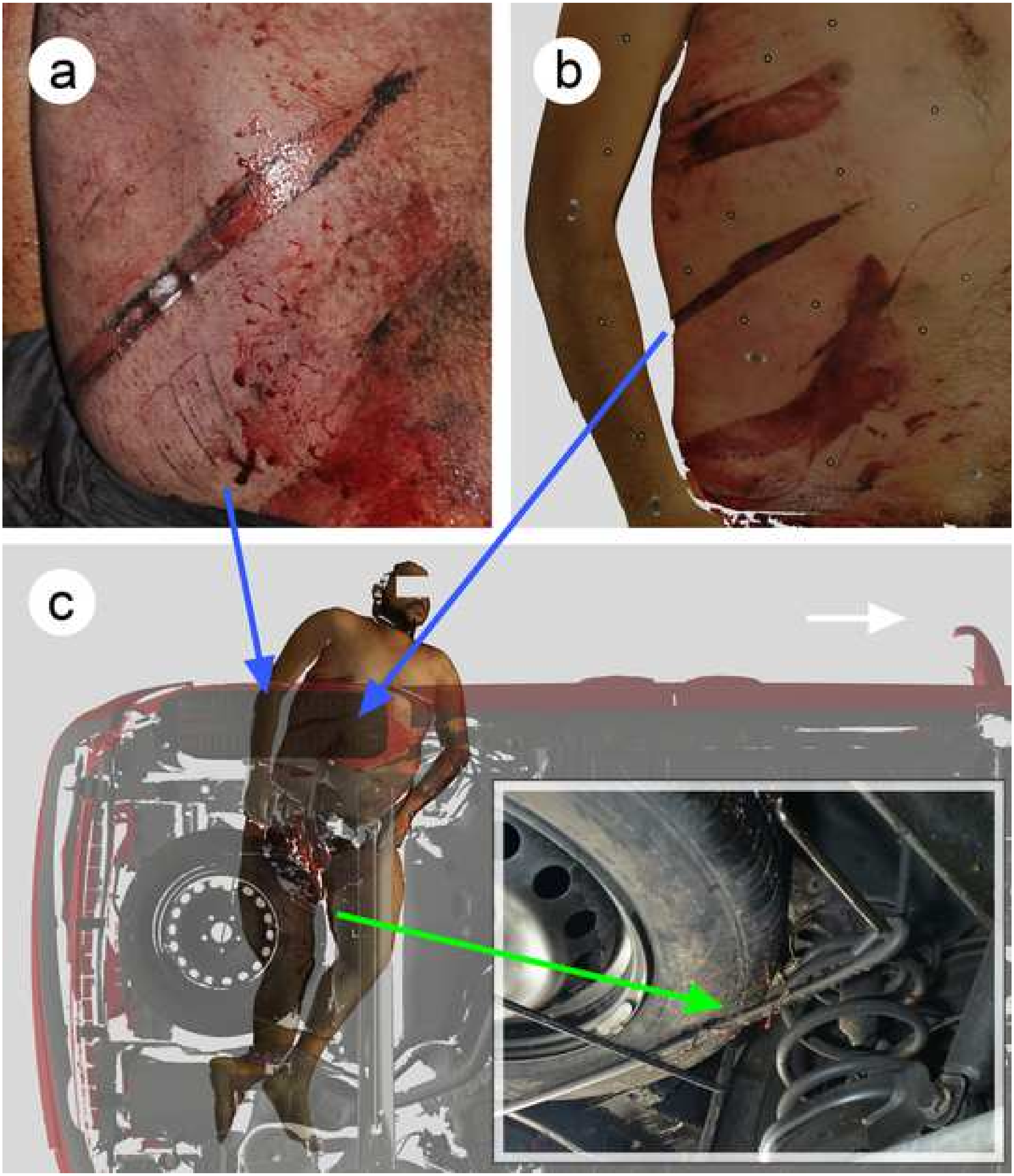

RESUBMISSION OF MANUSCRIPT No. FSI-D-19-00808 WITH THE REVISED TITLE

What happened before the run over? Morphometric 3D reconstruction.

Dear Mrs. Cattaneo,

First of all, we would like to thank the reviewers for their thorough work and constructive criticism on our proposed manuscript. In our revision we have tried to deal with all the comments and have changed the sections of the paper accordingly:

Reviewer 1 comments	**Answer**
However, for a small case series the number of figures (11 with more than 20 sub-figures) seems to be too high.	We reduced the number of figures from 11 to 8.
The paper seems to be more a case series than an original research article.	Thanks for this comment, we revised the text to work out the new possibilities and scientific evidence in run-over accidents (Discussion, section 4-7). This area was a topic in the 1980s, but since then this field was neglected. The reconstruction methods used today can contribute a huge benefit with additional results and lead to a better understanding of such accidents.
Reviewers 2 comments	**Answer**
1.There is an English language issue with the paper. A "roll-over" RTC to me is when the people are in the vehicle and the vehicle rolls over. However the paper refers to pedestrians who are "run over" i.e. the vehicle runs over them. This needs sorting to ensure the reader knows what the paper is about.	We changed the word “roll over” to “run over” and explained it in the footnotes as follows: “All run-over accidents presented in this paper are accidents where at least one wheel goes over a part of the body. In literature this type of run over is sometimes also called roll over.“
2.The last part of the abstract from "In the first case..to had to be clarified is not abstract and should be removed.	We removed this section and wrote a new sentence as follows: “Run-over accidents have received less attention than the topic of pedestrian, bicycle and motorbike accident analysis for which there is a large body of literature. Our goal is to add to the understanding of run-over accidents using morphometric reconstruction in order to improve their analysis in the future. The possibilities of morphometric reconstructions by means of 3D techniques in run-over accidents are wide-ranging and can provide new, unexpected and significant insights.”
3.In the introduction it is unclear why joint	That’s true, it was not clearly described. We

case evaluation is not possible. This needs explaining. In the results the text talks about left sided rib fractures yet Fig 6 shows right sided injuries.	changed the text and insert a new sentence to explain it. Thank you, we corrected left to right side.
4.In case two, considering the authors suggest the vehicle has run over the length of the body including the head there is little skeletal trauma as would be expected in such cases. This questions the validity of their reconstruction.	We insert the following sentences in the discussion of case two to explain this: „The lack of severe injuries that would usually be expected in cases of run-over accidents could be conclusively explained by the constellation (vehicle-victim-position) and the low speed of the vehicle during the run over.“ This is one of the novelties of the method, we can establish a run over based on all findings and traces and see that in some cases the skeletal trauma is not as severe as it would be expected. In the traditional way a run over was assumed also based on the severity of the skeletal trauma.
5.Not sure what "pocket formation" means	We changed this word to degloving (décollement).
6. How much did such a system cost and how long did it take. This is relevant to those considering adopting the system.	The costs are depending on the used 3D system and become cheaper every year. We insert the following sentence to say something about the cost and effort. "With the rapid development of hard- and software in the field of 3D technology, the equipment is becoming easier and faster to use as well as more affordable [25]."
7. There are errors in the references in terms of the correct referencing of journals and use of capitals.	We corrected these errors.
Although the authors present three cases to support their method I have to ask what the novelty is in this paper. I found simply looking at the images and descriptions I could have worked out what happened without the need for the graphical reconstructions. So what is the added benefit. Also the graphics are not novel. The book "The Virtual autopsy" contains a whole section on the use of such technology for road traffic investigation. The authors need to explain what is new and novel about their approach compared to that which some have already published.	We revised the text to work out the advantages and novelty of the morphometric reconstruction of run-over accidents and explained why the used method is so important in run-over cases.

We would like to thank the reviewers for their very constructive comments and suggestions. The textual changes made in consequence of these have improved the quality of our manuscript. We highlighted the textual change in the manuscript in yellow colour.

Thank you for your efforts.

Sincerely,

Ursula Buck

UB: Conceptualization, Acquisition of data, Analysis and interpretation of data, Visualization, Writing - original draft, Writing - review & editing, Project administration

KB: Writing - original draft, Writing - review & editing

LC: Acquisition and analysis of data, Visualization, Writing - review & editing

FG: Writing - review & editing

CS: Interpretation of data, Conceptualization

CJ:, Writing - review & editing