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Intuitive presentation of clinical forensic data using anonymous and person-specific 3D reference manikins

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ABSTRACT

The increasing use of CT/MR devices in forensic analysis motivates the need to present forensic findings from different sources in an intuitive reference visualization, with the aim of combining 3D volumetric images along with digital photographs of external findings into a 3D computer graphics model. This model allows a comprehensive presentation of forensic findings in court and enables comparative evaluation studies correlating data sources.

The goal of this work was to investigate different methods to generate anonymous and patient-specific 3D models which may be used as reference visualizations. The issue of registering 3D volumetric as well as 2D photographic data to such 3D models is addressed to provide an intuitive context for injury documentation from arbitrary modalities. We present an image processing and visualization work-flow, discuss the major parts of this work-flow, compare the different investigated reference models, and show a number of cases studies that underline the suitability of the proposed work-flow for presenting forensically relevant information in 3D visualizations.

1. Introduction

The analysis of forensic cases nowadays is based on different sources of digital information for example regarding the documentation of living victims' injuries [1–3], accident and crime scene reconstruction [4,5], or in-court presentation of forensic findings [6]. Usually, 2D photographs are used to document injuries, scenes, and forensically relevant events. In addition, the recent years have seen an increasing interest in medical examinations, i.e. 3D imaging modalities like Multi Slice Computed Tomography (MSCT) and Magnetic Resonance Imaging (MRI), in the context of post-mortem forensic investigations [7,8] and clinical forensic medicine [9]. By the use of these methods, a more complete impression of a forensic case can be obtained and additional information becomes available, information which might be invisible by sole investigation from the outside [10,20].

Collecting different sources of digital information about a forensic case (e.g. 2D photographs, 3D tomographic scans) obviously leads to the problem of limited and not necessarily overlapping fields of view of the image data. To be able to accurately depict structures of forensic interest, the need for high spatial resolution of image data arises. Unfortunately, this is accompanied by a restriction of the body area/volume that may be photographed/scanned. Reasons for this restriction are finite resolution of imaging devices, X-ray dose considerations in MSCT, a limited scanning time to prevent overstraining of (often traumatized) living subjects, and technical limitations in scanning protocols.

The two goals of collecting forensic findings from imaging based sources are to extract forensically relevant information (e.g. size and characteristics of injuries, directions of impact), and to present findings in court to support reports of forensic experts. In the present work we focus on the second aspect, which involves the need for forensically relevant imaging data to be clear, unambiguous, easy to understand, and hard to tamper with. Above all, there is the need to present an overview of forensic data in an intuitive manner, so that the user does not require a profound radiological or technical background to handle the data.

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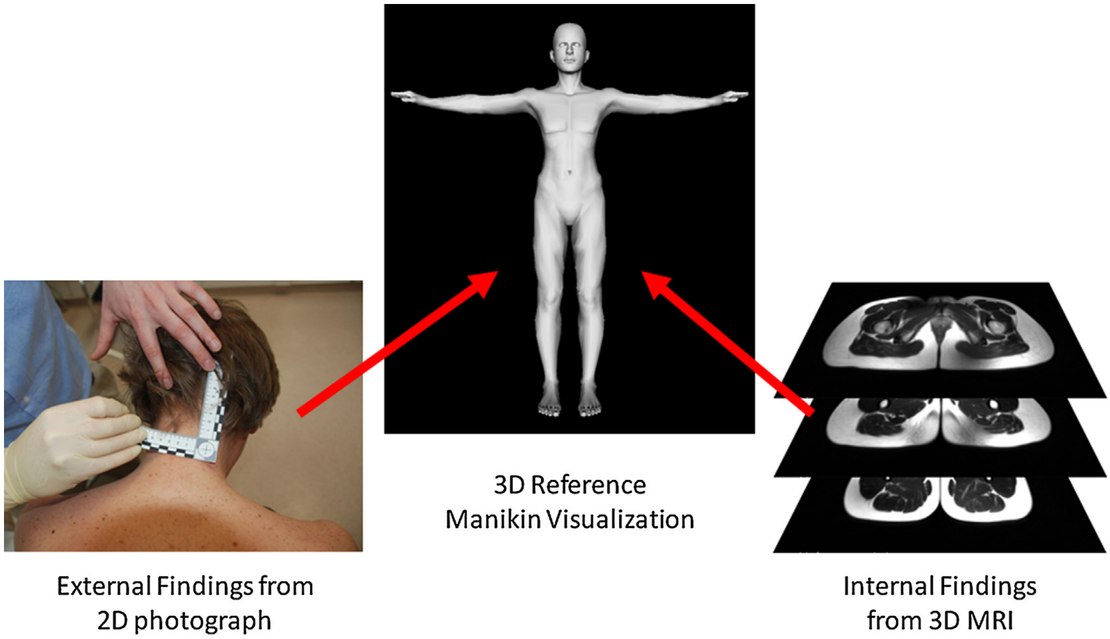

Fig. 1. Overview of the approach for generating a 3D reference manikin visualization that combines different sources of digital forensic information.

Other groups have proposed to provide an external reference frame by performing a 3D surface scan [8] based on photogrammetry and reference target markers followed by a surface scan using structured light patterns. Therefore they first take digital SLR photographs, that show the reference markers in overlapping images and photogrammetrically reconstruct the object coordinate system and camera locations using triangulation. Then a dense 3D surface reconstruction is performed based on the ATOS GOM[1] structured light system, that consists of a projection device and two cameras. Finally the 3D surface is embedded into the photogrammetric 3D coordinate system. The high resolution SLR color images of the subject can be used to texture the 3D surface scan, since the photogrammetric approach delivers the individual camera locations and orientations. Recent developments augment this setup with a robotic arm that steers the optical surface scanner to the scan locations [11]. A clear advantage of this setup is the direct correspondence of MSCT scan volume and 3D surface scan, since both measurements are taken sequentially without changing patient position. This state of the art setup achieves impressive and accurate reconstructions, however it is complex and rather costly to install at forensic departments. In this work we present a simple and cost effective scanning setup based on structured light using the Microsoft Kinect® device. It mimics the photogrammetric approach with a single device, that is simple to use and comes at a fraction of the cost, however, it is not able to perform an intrinsic registration of surface scan and volumetric scan as shown in [11].

Another idea for creating a 3D reference frame is to directly use the MSCT or MRI scanner to generate a 3D surface model of a person. The reconstruction of the body surface is easy due to the contrast of body tissue and air in both modalities. Since the person is scanned for the forensic evidence anyway, the additional effort is low. However, we will show in this work shortcomings of this approach.

We propose a solution to the problem of limited acquisition fields of view in the context of a forensic work-flow. A forensic work-flow may consist of the acquisition of digital information from photographs and one or more MSCT or MRI scans, the extraction of quantitative measurements of forensic relevance, and visualization that allows presentation of findings in court. For the latter purpose we use a 3D digital reference manikin model (DRMM) that combines 2D and 3D information sources from restricted fields of view visually by registration onto the DRMM. Fig. 1 provides an insight into this idea.

We define the following aims as prerequisites for a tool which, given several sources of forensic data, can be used to prepare forensic cases on the basis of a 3D DRMM.

- Intuitive presentation of various digital information sources in court.
- Easy-to-understand overview visualization of injuries and/or sequence of events for the medical layman, i.e. judges, lawyers, jury members.
- Ease of use for the forensic expert to prepare the visualization and analysis results.
- Use of existing data sources like already performed medical examinations with MSCT or MRI, or photographs from external sources (this external data often does not adhere to conventions used in properly prepared and executed forensic examinations).
- Little to no additional effort for the often traumatized person in the case of living victims.
- If required: Anonymization of the victim.

The following sections present the proposed work-flow along with some case studies, which illustrate the described approach. Section 2.1 gives a description of the 3D DRMMs we have investigated, while Section 2.2 illustrates the work-flow needed to enrich the DRMMs with forensically relevant findings, here the technical aspects of 3D–3D registration, 2D–3D registration, and manually drawing injuries are described. Section 2.3 presents forensic cases, that were prepared with our software using 3D DRMMs, with results given in Section 3. A discussion and conclusion of the established work-flow in a forensic context is given in Sections 4 and 5.

2. Materials and methods

We define a forensic workflow as a process which consists of a forensic expert who analyzes and prepares a case in an offline step to come up with a case description and an accompanying visualization, and an in-court presentation where the visualization supports the forensic findings (see Fig. 1 for the idea and Fig. 9 for an example). A work-flow is proposed that connects sources of

[1] http://www.gom.com

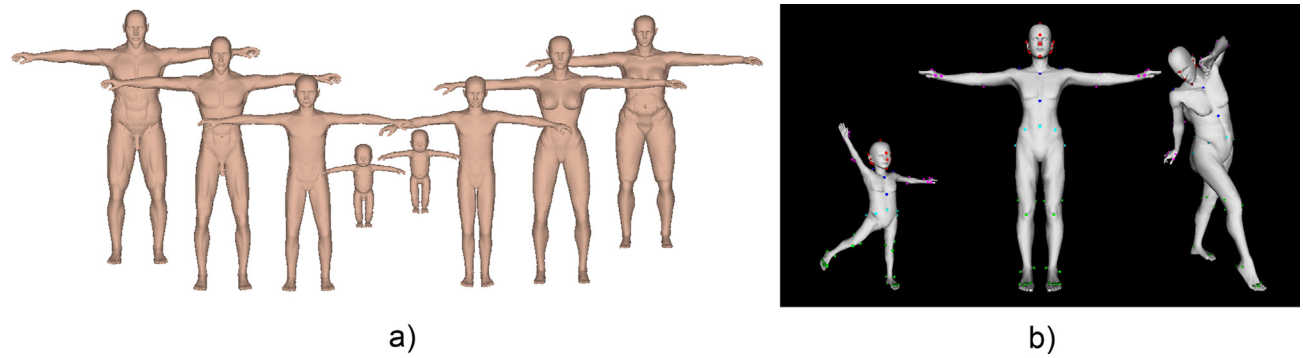

Fig. 2. (a) Models of different ages, genders, and body composition, provided by the BurnCase 3D software. (b) Makehuman reference models with markers, body posture animation is possible using the Animorph software package.

digital information and produces a generic 3D DRMM visualization based on this data. After a data acquisition step, involving MRI/MSCT scans and/or digital photographs, the first step is the selection of a 3D DRMM, i.e. either a generic, parametric 3D polygonal model (representing one of different genders, ages, and body composition), or a patient-specific model. This choice has to be made early on in the preparation of a case, since patient-specific models require additional patient scanning effort. Then, 2D and 3D data are automatically registered to the 3D DRMM to provide a common coordinate system for injury visualization. Registration is done marker-based or manually first, with a refinement step and adjustment of different joint angles, in order to optimally resemble the given case data. Manual interaction tools are proposed to mark exterior findings of injuries, in case of failure of the automatic registration.

2.1. 3D digital reference manikin models

The choice of the 3D digital reference manikin model (DRMM) is a crucial part in the proposed framework. A polygonal 3D model is required for visualization, however, in order to adjust this model to a specific forensic case reconstruction, a certain degree of flexibility in deforming the model and modifying body parts is needed. Three possible methods of establishing a 3D DRMM were investigated, a generic model with no relation to the patient, and two patient-specific models, a whole-body MRI scan, and a 3D reconstruction of the patient based on structured light.

2.1.1. Generic 3D model

A generic model automatically provides an anonymized, abstract visualization of a patient/victim at the cost of a lower accuracy concerning the real proportions of the body. Two possible candidates for a generic 3D model were identified. Firstly, the SCAPE method [12], which uses a 3D statistical shape model for animation and deformation, and secondly, a fixed human 3D model (see Fig. 2b) combined with an animation method, which was found in the Makehuman package[2]. Although the statistical shape model would better deal with the problem of adapting models to patients and patient postures, its need for a very extensive database of 3D person scans in different postures to train the model prevented its use in our case. Thus, the freely available Makehuman model was chosen and later extended to different genders, ages, and body compositions with the help of the commercial BurnCase 3D software package [13] (RISC Software GmbH)[3]. Especially the lack of baby and children models was compensated by the BurnCase 3D model data. In Fig. 2a an overview of the range of possible models is shown. The possible variability in body posture of the Makehuman model is especially illustrated in Fig. 2b.

2.1.2. 3D patient-specific model from whole-body tomographic scan

To use a whole body MRI scan [14] is an option if a person will be scanned for internal findings anyway. The air/skin interface gives a good contrast in the MRI signal for standard MRI sequences. Therefore a simple segmentation of the MRI scan into body and air regions was performed. The volumetric segmentation of the body was converted to a 3D polygonal model by the Marching Cubes [15] algorithm. For the MRI scans, head, neck, body and spine coils were used with a T2w HASTE sequence in coronary orientation (*TR*/*TE* = 1800/106 mm, slice thickness 5 mm). The acquisition time was 20–30 min, involving a few breath-hold steps. Note that in post-mortem cases an MSCT scan may be used instead of MRI, leading to an even simpler segmentation of the skin/air border due to the high possible radiation dose. However, since this work focused on living cases, no further investigations of MSCT data were performed.

2.1.3. 3D patient-specific model using structured light

Reconstruction of 3D models using photogrammetry is a well known method in forensic sciences [16,17,4,5]. Possible installations range from costly setups combining MSCT and robot-assisted structured light based surface reconstruction [11], which promise highly accurate scans, to low-cost solutions using a digital SLR camera to take a large number of color photos and reconstructing the 3D surface with inexpensive software like Agisoft PhotoScan. In this study, an alternative setup using the Microsoft Kinect device was investigated to perform a low-cost 3D scan using a structured light approach. The Kinect device originates from the computer games industry, where it is used as an input device for body poses and gestures, i.e. as a user interface sensor. This sensor tracks user motion by a depth-based reconstruction of the person in front of the projector/camera system. Depth is determined via triangulation by projecting an infrared light pattern on the user and recording the pattern with an IR sensor of 640×480 pixels resolution at a framerate of 30 fps. Reconstruction software is able to compute a polygonal 3D model from the thus generated point cloud [18]. The accuracy of the Kinect has been evaluated in [19], where the authors conclude that the depth accuracy lies between 2 mm at 1 m distance to the sensor up to 2.5 cm at 3 m distance. The in-plane localization error lies between a few millimeters at 0.5 m distance to 4 cm at 5 m distance to the sensor. The works of Smisek et al. [22] and Chow et al. [21] report similar results, with [22] stating that the Kinect reconstruction of a test object shows a root-mean-square error of 11 mm compared to a laser scan using a Leica ScanStation 2. In our investigated setup a 3D model of a patient was created using a turntable setup (see Fig. 3) in a matter of minutes by combining three scans in sequence with the Kinect

[2] http://www.makehuman.org
[3] http://www.burncase.at

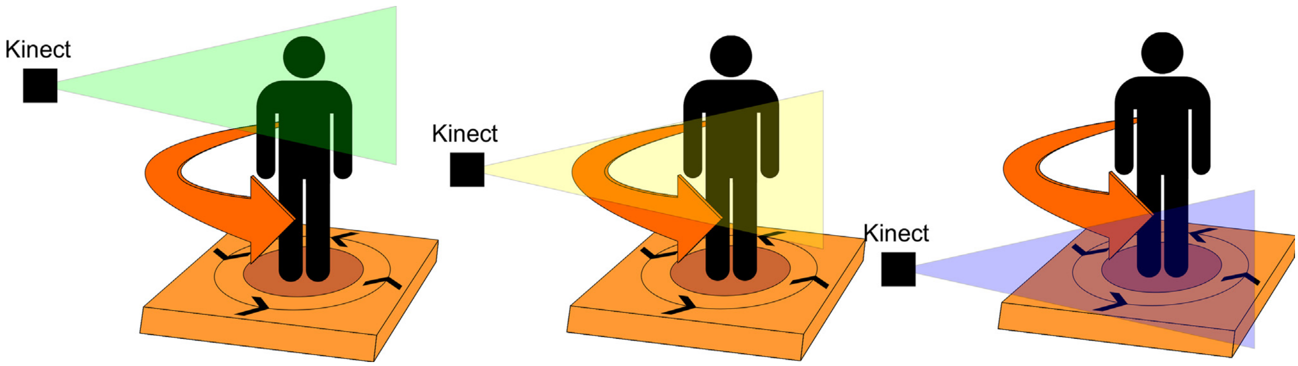

Fig. 3. Setup for Kinect based DRMM construction. A scan consists of three turns with the Kinect device at different heights, while the person is standing on a turntable.

device placed at different heights. The turntable had a diameter of 60*cm* and was powered by an electric motor to allow continuous rotation at a speed of one to two revolutions per minute, a duration which patients are generally able to stand still. The distance of the Kinect to the scanned object was between 0.75 m and 1.75 m to keep the reconstruction error low in accordance with [19]. The Kinect setup performs a calibration step internally, and the reconstruction is metric due to its stored reference projection pattern, that is used for disparity computation. According to the findings in [18,19,21] we compared this setup using the internal Kinect calibration with a second variant, where we additionally performed a calibration of depth and color images externally. Therefore the raw video streams of the Kinect were extracted and the publicly available code for calibration from [20] was used to correct each image of these video streams before reconstructing the depth information using the ReconstructMe SDK[4]. The reconstructed 3D model needed some manual post-processing to remove holes and unneeded structures and to generate a watertight mesh (see Fig. 7b). Additionally it is possible to merge external photographic images of the person with the 3D model (see Fig. 8), or to use the lower resolution color information from the Kinect device for creating realistically looking 3D models if wanted. Total costs of the Kinect plus turntable setup and ReconstructMe SDK amount to ca. 750 Euro, thus enabling a low-cost real-time 3D scan solution.

To evaluate the accuracy of uncalibrated (i.e. relying solely on the internal hardware calibration) and externally calibrated Kinect scan, we created an accurate reference scan of the torso of a display dummy (see Fig. 12) with a Breuckmann[5] OptoTOP-HE commercial structured light scanner as a baseline to compare our reconstructions to. A volume of 55 cm $\times$ 40 cm $\times$ 30 cm at a distance of 1*m* was used for this scan. The technical specifications of this scanner shows a sub-millimeter reconstruction accuracy for objects of this size. Comparison was performed by first globally registering Kinect scan and reference scan using Iterative Closest Points [24], followed by a computation of the distances between all points from the Kinect scan to the nearest point on the reference scan (which is represented with more detail using approximately twice the number of points as a result from the scanning procedure). No further smoothing was performed. The statistic of the distances are given as mean distance, standard deviation and maximum distance, thus resembling the error in accuracy of the respective Kinect scan. We also investigated a setup using a series of approximately 170 calibrated digital SLR images of the display dummy, and reconstructing a 3D model with the multi-view stereo software Agisoft PhotoScan[6] for comparison to a different low-cost 3D reconstruction strategy.

[4] http://reconstructme.net
[5] http://aicon.de
[6] http://www.agisoft.ru

2.2. Forensic presentation work-flow

Besides the 3D DRMM, a basic ingredient of the work-flow generating a reference manikin visualization is the registration of different sources of forensic information to the DRMM. Informally, registration is defined on a pair of input data sets as finding a transformation (i.e. a mapping of coordinates of an input space to coordinates of an output space) by minimizing a measure of dissimilarity, such that corresponding anatomical parts are mapped to each other [23]. For a specific instance of a registration problem (e.g. 3D–3D registration) a transformation model and a dissimilarity measure, e.g. a distance between corresponding points in the pair of input data sets, have to be defined. In this study only rigid and similarity transformation models, that allow some degrees of freedom in translation, rotation and isotropic scale, were used. Minimization of the dissimilarity measure is an iterative process that has to be initialized properly and eventually reaches a local optimum of the given energy function (i.e. the dissimilarity measure).

In the subsequent sections the details of the used work-flow are presented (see Fig. 4). Additional information on the algorithms can be found in [30].

2.2.1. Data acquisition

Focusing on cases of the living, tomographic imaging of injuries and hematoma was performed with MRI protocols that separate fat and water using high resolution turbo spin echo sequences, proton density weighting and fat suppression (SPAIR). Markers which are visible in photographs as well as in the MRI signal were used. These were attached to anatomically prominent locations. Locations were manually marked on the 3D digital reference manikin models (see Fig. 2b).

2.2.2. 3D–3D registration

A three-step procedure was used for the registration of 3D volumetric data from MRI/MSCT to a 3D DRMM. To get an initialization the markers located on the MRI scans were registered to the markers that were manually placed on the 3D reference model. Marker-based registration for the estimation of a similarity transformation model can be solved directly by computing the 3D translation vector, isotropic scaling factor, and rotation matrix in a Procrustes alignment step [23]. This initialization is only a rough approximation, due to its dependency on the placement of markers on the reference model and the patient, and due to small anatomical differences between reference model and patient. To improve the result Iterative-Closest-Point (ICP) surface registration [24] over the seven unknown degrees of freedom of an isotropic similarity transformation model was used. The ICP algorithm is an iterative method for surface registration that switches between two stages, point correspondence determination and point-to-point

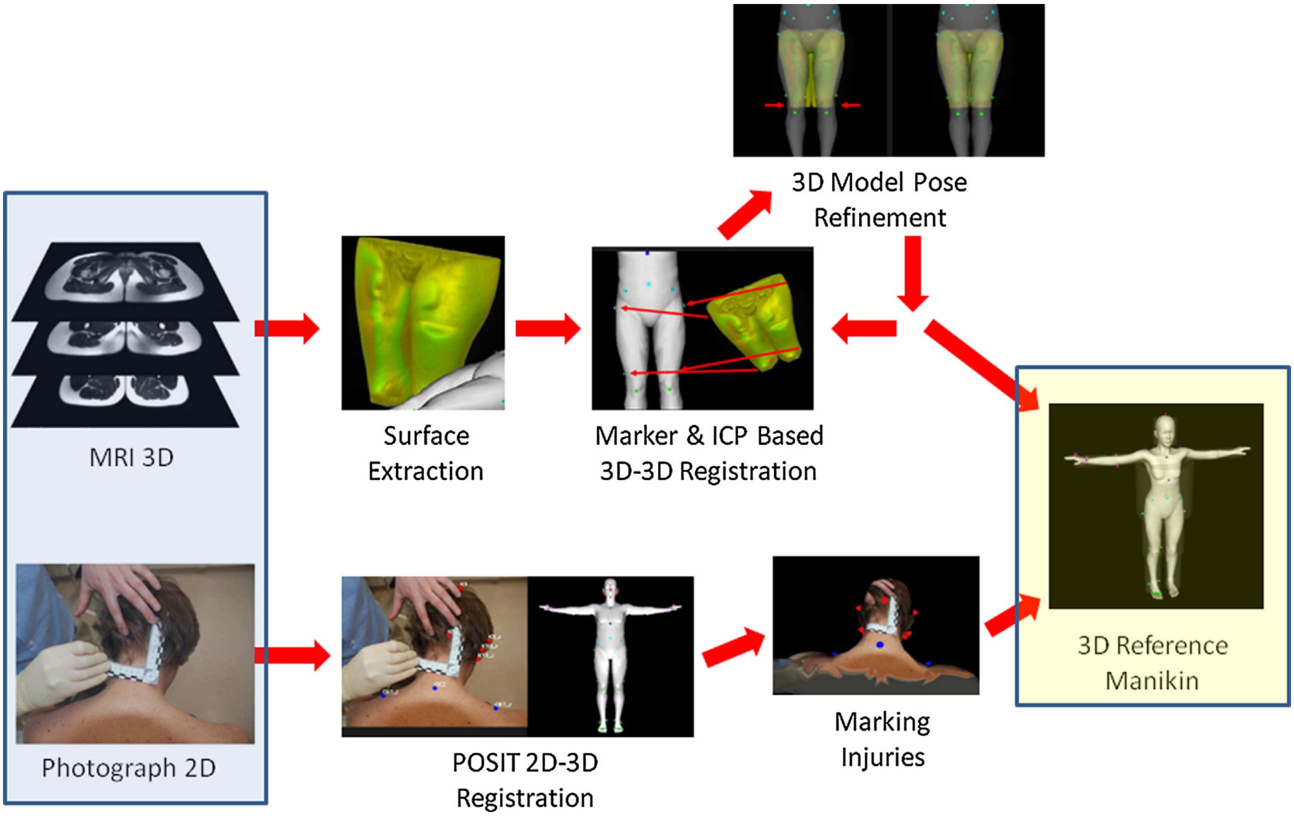

Fig. 4. An overview of our work-flow for visualizing different sources of information in a common intuitive 3D reference manikin model.

registration, until convergence. In order to extract the outer skin surface from the MRI scan, a thresholding based segmentation was performed, followed by a surface extraction step that generated a 3D polygonal model similar to the 3D DRMM. For surface extraction the Marching Cubes algorithm [15] was used, and the number of generated triangles (Marching Cubes tends to produce a very large number of polygons) was decreased by a method that minimizes the quadric error metric [25]. With this approach the polygonal result of the Marching Cubes step was reduced from around 95,000 vertices and 190,000 triangles to 2000 vertices and 3000 triangles without a significant loss of details. The final step of the registration procedure accounted for differences in body posture between the 3D reference model and the 3D surface extracted from the volumetric scan. For this purpose the joints of the 3D reference model were adjusted using kinematics calculations.

2.2.3. 2D–3D registration

The forensic presentation work-flow requires software that semi-automatically maps 2D photographs of e.g. injury locations onto the 3D reference manikin model (see Fig. 5). A tool was developed which requires only a small amount of user interaction from a forensic expert to identify marker locations in a given 2D image. These collected marker points, which were manually selected in a graphical user interface (GUI), were used to establish a 2D–3D registration transformation with the help of the POSIT algorithm [26]. POSIT assumes a scaled orthographic projection (SOP) model for the mapping of 3D points on the 2D image plane, which is essentially a parallel projection followed by a scaling transformation. This involves a weaker model than using a full projective transformation for the interior camera parameters, however, the benefit is to be able to work with images from uncalibrated cameras. Thus, images from different sources can be used, sources which possibly did not strictly follow conventions on how to take photographs or how to calibrate the camera setup. The drawback of the simplified camera projection model is that images with perspective distortions are problematic. POSIT requires a minimum of four corresponding 2D–3D point pairs to give a solution to the unknown projection and orientation parameters. These point pairs were chosen in the GUI by the forensic expert and labeled according to the marker definitions (Section 2.2.1). POSIT iteratively refines the unknown projection parameters in a least squares manner. The more point pairs the user provides, the more stable the mapping becomes. Registration quality directly depends on the quality of the choice of marker locations, this was experimentally validated using positional noise in the work of [30].

After the POSIT step the posture of the reference manikin model may be further refined to improve the accuracy of registration. The method according to Taylor [27] was used, taking into account the foreshortening between each of the body segments in the 3D model and its 2D image. Here again SOP is the projection model. With the established projection of 2D image to 3D model, the final step was to transfer the image into the texture space of the 3D DRMM. The texture space is a normalized 2D coordinate system (see Fig. 6a), which is used for applying the color appearance to the triangles of the 3D mesh. Fig. 6b illustrates the mapping between a view of the projected 2D image and the normalized texture space, requiring the computation of texture coordinates u, v. This computationally intensive projection process, that extensively uses bilinear interpolation, is performed in hardware on the graphics adapter.

2.2.4. Manually marking injuries

There are some cases, when the 2D–3D registration is difficult or even impossible, i.e. if the scaled orthographic projection model is significantly violated, or if the forensic expert is not able to identify the minimum number of four required marker locations in the 2D image. For this purpose a fully manual method to draw injury locations onto the 3D DRMM was provided (see Fig. 6c). By

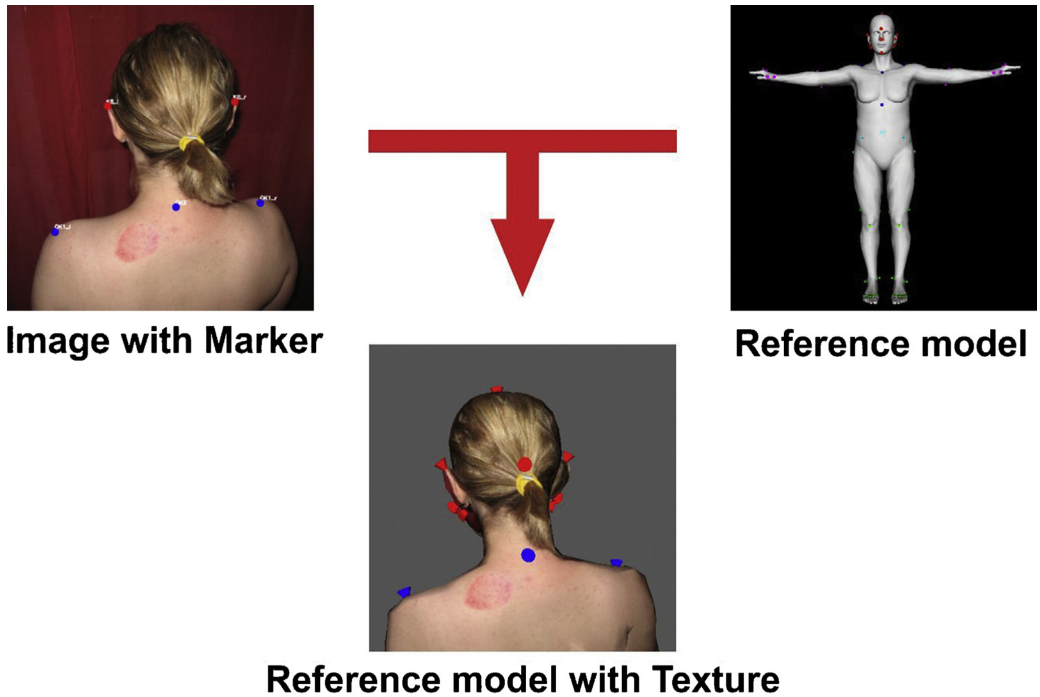

Fig. 5. Overview of the 2D–3D registration. In the 2D image markers have to be identified. These markers are used to map the 3D reference model onto the image. The 3D model can now be painted with information from the 2D image (texturing).

enabling free translation and rotation of the 3D DRMM, interactive drawing of polygonal areas directly on the 3D surface became possible, that allows labeling of distinct injuries. Additionally, a mechanism was established to highlight and label injury regions in the photographs by drawing polygons into the image. Then these polygonal regions were projected onto the 3D DRMM according to the freely adjustable viewpoint direction and orientation. The projection of the polygonal image selections are transferred onto the 3D DRMM with the same procedure as in Section 2.2.3, where the view-dependent projection is used instead of the marker-based projection.

The accuracy of using textures for the color appearance is limited by the discrete texture size rather than by the number of faces and vertices of the polygonal mesh. The body surface of a man with a height of 180 cm and a weight of 75 kg was estimated according to DuBois et al. [28] as 1.9 m^2. Approximately 60% of the rectangular texture space can be used for encoding skin colors of the body surface. Thus every pixel of a texture with the default quadratic texture size of 2048 $\times$ 2048 represents an average body surface of 1 mm^2. Thus representing images and polygonal structures in texture space theoretically allows depiction of small structures in the mm range.

2.2.5. Visualization framework

The interactive, integrated visualization software framework presented in [29] was used for visualizing 3D polygonal models as well as 2D photographs and 3D volumetric image data sets from MRI scans in order to render result images capable of visualizing forensic information from different modalities at the same time in a single scene.

2.3. Cases

Two exemplary cases were prepared. Our forensic presentation work-flow was applied to both cases to generate visualizations suitable for in-court presentation. Further, two volunteer MR test scans (male, 1.84 m, 82 kg, female, 1.67m , 61 kg) were performed in a whole-body MR scanner.

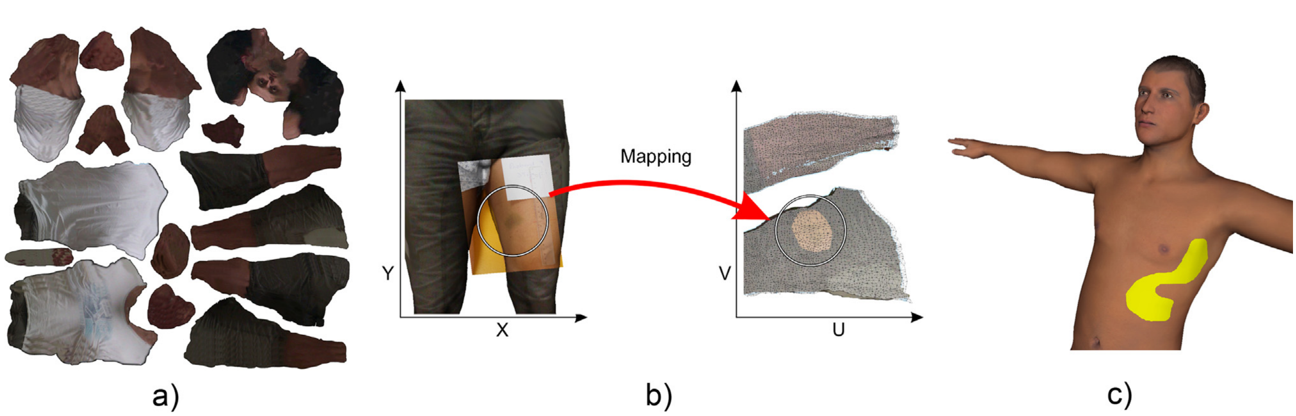

Fig. 6. Texturing of 3D DRMMs (a) An example texture used to improve the appearance of the DRMM. (b) Mapping from image space to texture space via the projection of the image onto the 3D model (c) Manually marking regions using the texture of a generic 3D DRMM (e.g. for injury locations).

2.3.1. Case 1

A 23 year old man has told that he was at a nightclub when a doorman requested him to leave the place. He has stated that, as he refused to leave, a fight broke out between him and the doormen during which he was grabbed by the upper arm and thrown with his back against a wall. He has told that he was hit in the face and on the upper body, and strangled by the bend of the elbow. At the external examination, a reddening of the skin of the neck was found. Bruises and abrasions were detected on the left forehead and at the lower lip, above the left clavicle, and on the left side of the chest as well as on the left side of the back and on the right arm. In the MRI examination the next day no injuries were found.

2.3.2. Case 2

A 2 month old baby was brought to the hospital by its mother to examine a swelling on the ear. As this swelling turned out to be a massive hematoma of the ear, X-ray examinations were performed due to the suspicion of child abuse. A fracture of the skull on the back of the head as well as numerous fractures of the ribs, the clavicles, the left shoulder blade, both forearms, the left upper leg, and both lower legs were detected. In an MRI examination bleedings were found in the posterior brain as well as in the frontal lobes. Externally, additional hematomas were found on the face. Both parents said that they did not abuse the baby, and that they had no idea how the child had been injured. Based on the characteristics of the findings the injuries were due to multiple violent events which presumably started when the child was about 3 weeks old.

3. Results

3.1. Comparison of different 3D DRMMs

Three different ways of generating 3D DRMMs, a generic model, a patient-specific model from an MR scan, and a 3D model from a structured light setup were investigated to compare their suitability as a 3D DRMM. While the generic model (see Fig. 6c) shows the least effort in setup, the other two methods require specific scan sessions with the patient.

Theoretically, the MR whole-body scan seems to be not much of an additional effort in some cases, since an MR scan is probably performed to investigate e.g. hematomas and other internal injuries. However, in practice we have found a number of obstacles that prevent the use of MR whole-body scans. The protocol for whole body coverage is quite long (20–30 min), thus significantly prolonging total scan time. The setup uses special coils for all body regions, which means that the patient is strongly fixated, a condition which can be problematic for traumatized persons. The major limitation is the restricted field of view that is achieved. The test scan of the male volunteer is shown in Fig. 7a, with a volume rendering of the skin surface. As it was not possible to move the table over the full height of the volunteer, the feet could not be reproduced on the final scan. Additionally, in the shoulder area SNR was too low at the borders of the table gantry to reconstruct the skin surface due to *B*0 field inhomogeneities. Further inaccuracies were due to deformations caused by the volunteer lying on his back on the table. The resulting whole-body MR scan of the smaller female volunteer showed that the whole extent of a small person may be scanned accurately, however, the elbow regions could still not be correctly reconstructed.

Despite the Kinect based structured light setup requiring more effort in terms of setup, the resulting quality of the 3D model is higher than the MR whole-body scan model and seems well suited for presentation of a patient-specific model in court. An example is shown in Fig. 7b, which presents the same male volunteer as in Fig. 7a. It is difficult to get a tight mesh reconstruction at the bottom of the feet, as this region is never scanned. However, as it can automatically be corrected by a planar approximation of the feet surface, this problem can be neglected.

Our experiments concerning the accuracy of the Kinect scan have shown that with our carefully designed turntable setup and our scanning distance between 0.75 m and 1.75 m, it is possible to achieve a mean distance of the ReconstructMe model to the high quality Breuckmann reference scan of 2.2 mm, with a standard deviation of 2.0 mm and a maximal distance of 22.4 mm. After additionally performing an external calibration step, we have seen that this accuracy improves to (mean/std/max) distances of (1.7 mm/1.2 mm/9 mm). All these results were produced by averaging the distance computations of three independent scanning experiments, respectively. Results for the 3D reconstruction using Agisoft PhotoScan are (mean/std/max) of (1.1 mm/ 0.6 mm/5.9 mm). Visual results of these different reconstructions can be found in Fig. 12, where we show the models compared to the reference scan and also the details of the display dummy hand. The color-coded representation depicts the variation of the reconstruction error over the 3D models. While the accuracy of the Agisoft result is better than the externally calibrated Kinect setup, we identified a number of problems with this approach due to an increased effort in the required setup. Firstly, a large number

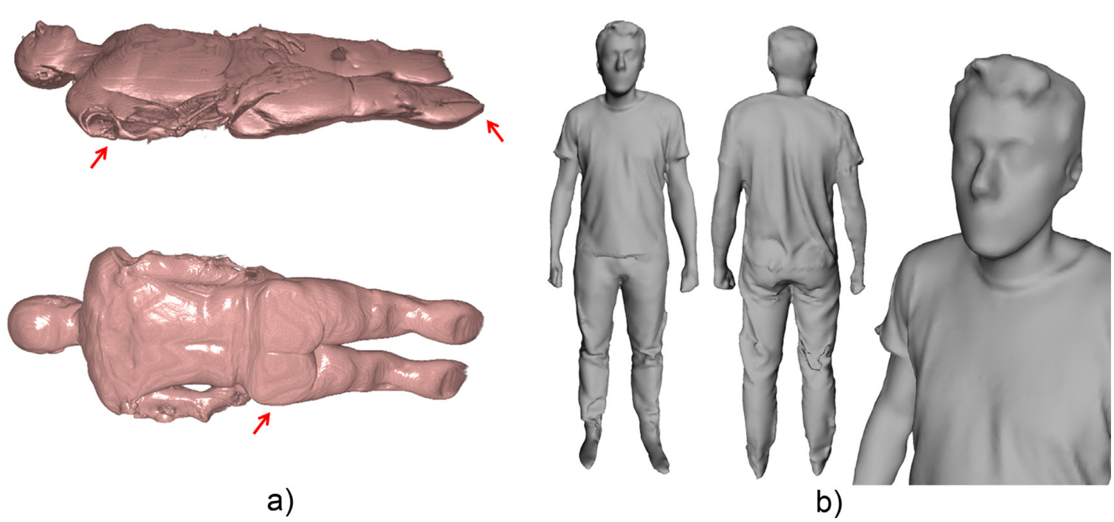

Fig. 7. Comparison of a 3D DRMM from a male volunteer of height 184 cm. (a) volume rendering of a DRMM from a whole-body MR scan, note the problematic regions, indicated by the arrows. (b) a 3D scan from the externally calibrated Kinect based structured light setup.

Table 1
Comparison of different DRMM techniques, with respect to the issues raised in Section 1. Concerning anonymization for the models using MRI and Kinect a black bar covering the eyes has to be added manually.

	Generic	MRI	Kinect
In-court presentation possible	Yes	Restricted	Yes
Easy to understand	Yes	Yes	Yes
Easy to prepare	Yes	No	Yes
Use of existing data	Yes	Yes	Yes
Effort for patient	No	High	Medium
Anonymization	Implicit	Add a bar	Add a bar

of SLR photos from different angles were required (around 170), and for all of them mask images to separate the display dummy from the background had to be generated to prevent the feature matching from focusing on background structures. This was done by placing the display dummy in front of a green wall. Secondly, the multi-view stereo approach has problems with untextured surfaces, due to its object feature matching step. Such features need to be robustly extractable on different overlapping images. Further, the reconstruction of the 3D model takes many hours of computation time, while with the Kinect setup we get immediate feedback during scanning from the ReconstructMe software. Finally, when translated to the practical scenario of patient scanning, the whole procedure of taking the photographs takes longer compared to the Kinect setup, which poses problems concerning the ability to stand still during the scan.

In Table 1 an overview of the suitability of the three DRMMs with respect to the criteria presented in Section 1 is given.

3.2. Patient-specific model example with a hematoma

In Fig. 8 the composition of the final 3D model of the Kinect scan is shown for one female volunteer including texture, which is derived from four photographs taken from different directions. The photographs were obtained during the 3D scan, while the person was standing on the turntable. Note that the use of external photographs is optional, for an overview the untextured 3D model is sufficient.

Fig. 9 shows a Kinect based patient-specific model, where the photograph of a hematoma of the left arm was registered to the 3D models' texture (see Fig. 9a), and the MR scan of the hematoma was registered to the 3D mesh, thus putting all findings into the correct context. The markers used for the registration are not shown, to provide a less cluttered visualization. All relevant information is depicted in one intuitive visualization, which is suitable for in-court presentation. Note that here we did not use a textured 3D model to prevent generating the illusion of high model accuracy potentially supporting measuring injury sizes directly from the model. Additionally, the software framework enables the quantification of potentially required internal parameters, e.g. the size and volume of a hematoma (Fig. 9f) from the MR scan using a segmentation algorithm [29].

3.3. Case studies

3.3.1. Case 1

The generic DRMM from the Makehuman project was used to create the scene for the visualization of case 1 (Fig. 10). A number of external findings were located and photographed, and placed into the texture of the generic DRMM. The generic model was processed with the patients' face, since there was a photograph available. The injuries in the neck region can clearly be identified in the 3D DRMM, as well as the injury at the back and the bruised lips. The suspicion of a strangulation was not confirmed by the MR scan where no internal findings were located by two radiologists.

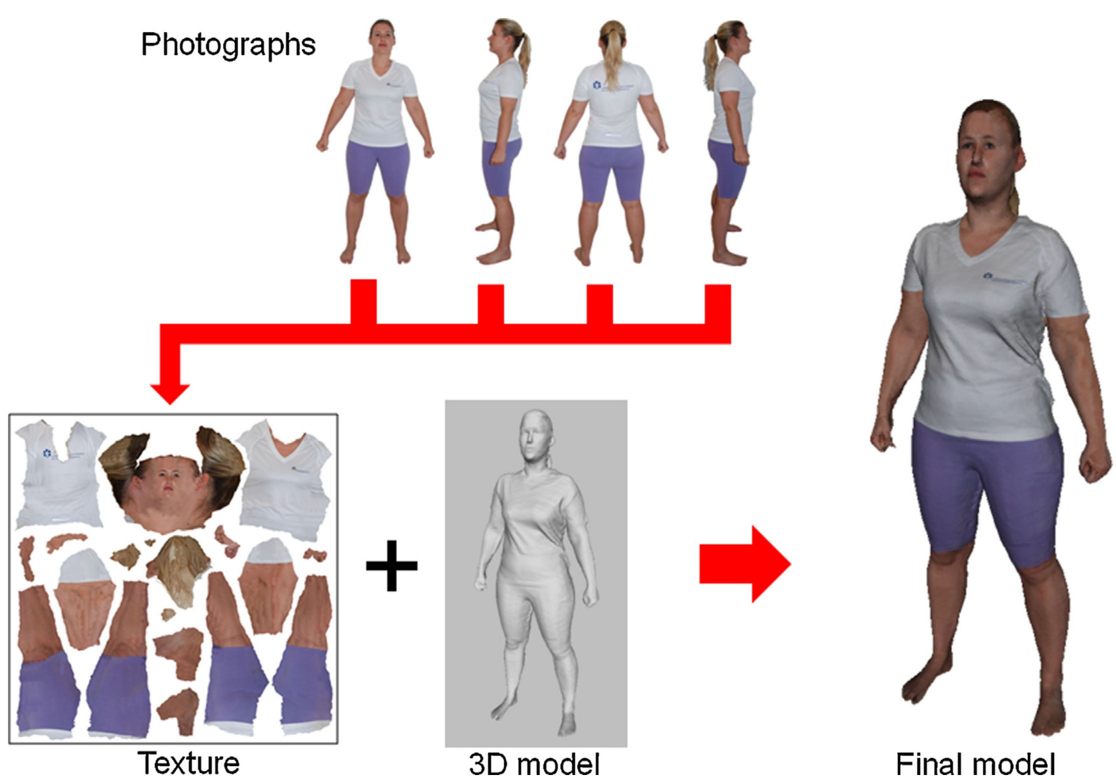

Fig. 8. Patient-specific model generation. The 3D model from the Kinect scan may be combined either with the color information from the Kinect camera, or with images from an external camera, which can be used for texturing the model to improve the qualitative visual appearance. However, the high resolution of the photographs may create an illusion of true-to-scale and color accuracy, which is not valid for our Kinect setup, therefore, no measurements should be done on these models.

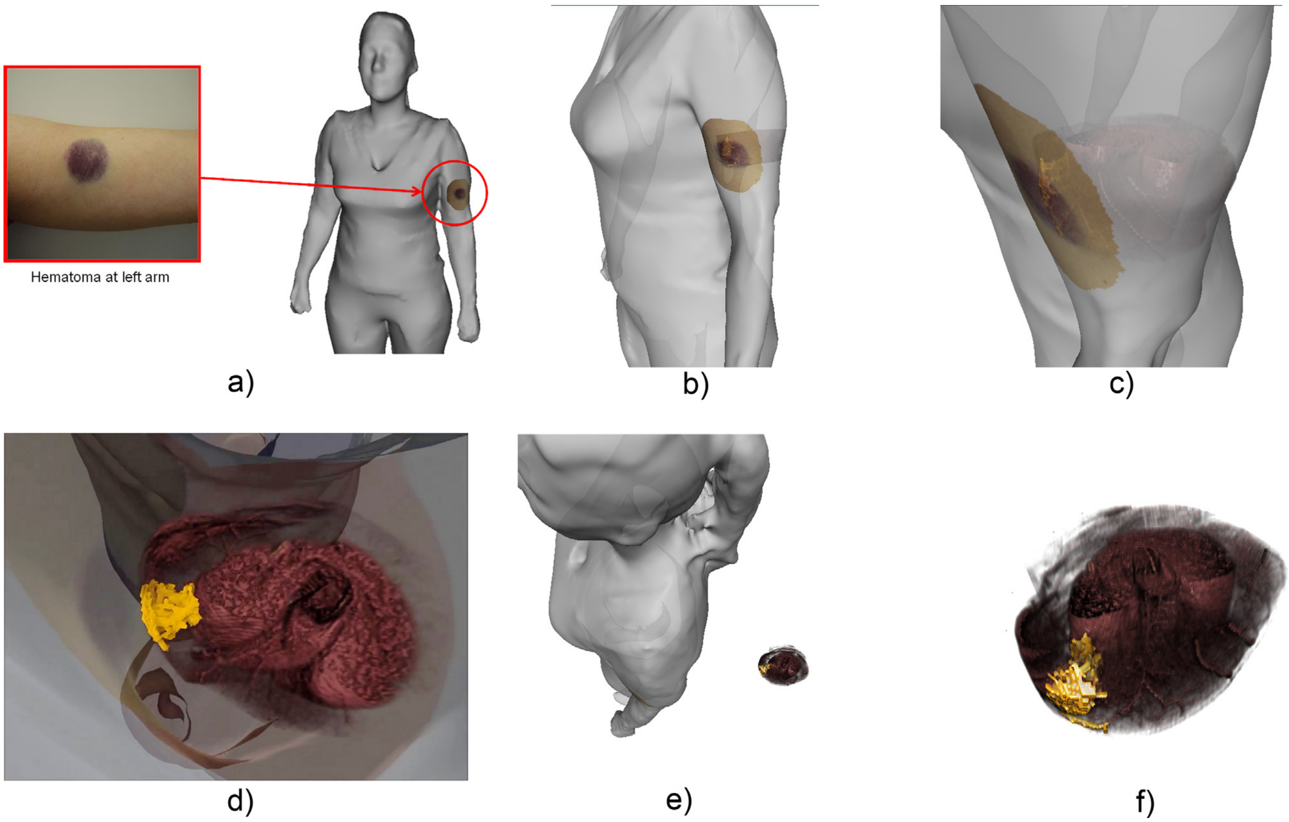

Fig. 9. Example of a patient-specific model involving a 3D DRMM, a photograph, and an MR scan of the hematoma. (a) The photograph is registered onto the 3D model and painted into the texture. (b) The combined visualization shows the injury from different angles. (c) The 3D DRMM is shown transparently, to provide a clue about the internal finding. (d) We are now inside the DRMM, investigating the volume rendering of the MR scan. (e) Interaction with the visualized scene allows disconnecting the MR scan from the model. (f) Close-up on the MR scan with the yellow structure being a segmentation of the blood pool that allows quantifying its size.

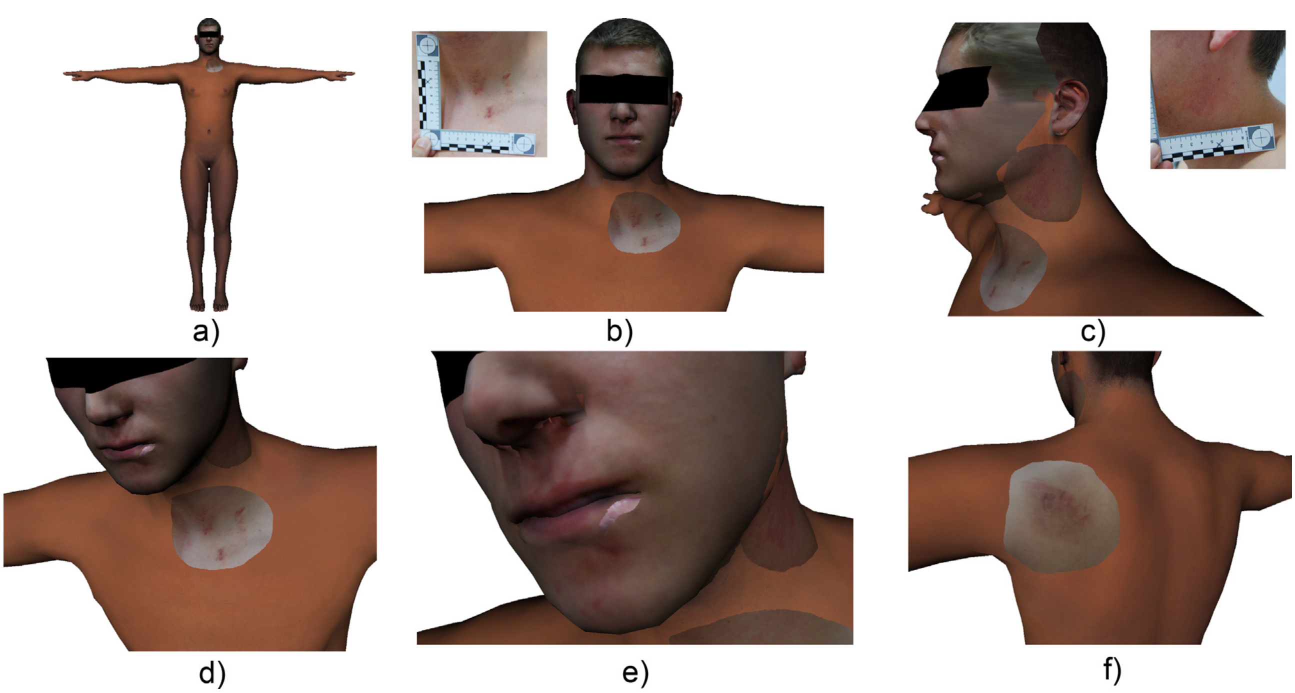

Fig. 10. Case study 1. A case with suspicion of strangulation. (a) An overview of the injuries, presented in the context of a generic DRMM. (b–d) Injuries in the neck region. (e) A lip injury. (f) Bruises on the back. No findings in the MR scan supported the suspicion of strangulation.

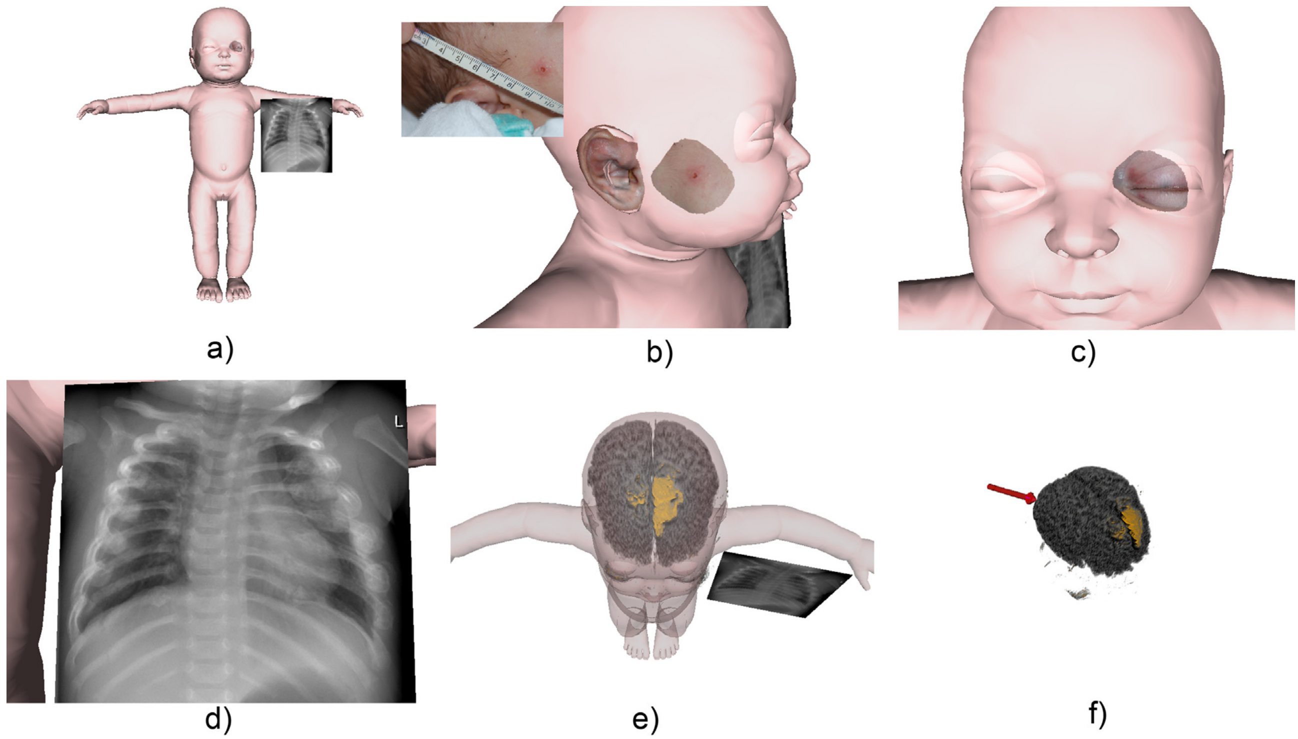

Fig. 11. Case study 2. A 2-month old baby with suspicion of child maltreatment. (a) An overview visualization of our generic baby DRMM, together with the X-ray image of the thorax. (b) Bruises on the right cheek and the right ear. (c) A bruise on the left eyelid. (d) The thorax X-ray shows several broken ribs, indicating severe shaking. (e) A transparent view of the baby skull, the brain MR scan becomes visible. The massive hematoma is in yellow. (f) Presumed impact direction causing the hematoma.

3.3.2. Case 2

A dedicated baby model, provided by RISC Software GmbH as a part of their software BurnCase3D, was used to show the internal and external findings of this case of severe child abuse (Fig. 11). Photographic findings of a bruise on the right cheek, a hematoma on the left eye lid, and an ear hematoma were integrated. X-ray images of the ribs and extremities, and an MR scan of the brain revealed a large number of internal injuries. A series of fractured ribs can be seen in the X-ray image, while the MR data show severe intracranial hemorrhage. In the proposed visualization framework, the proper placement of findings into its reference coordinate system is possible.

4. Discussion

The use of 3D DRMM's allows an intuitive understanding of injuries and their locations for an overview presentation of forensic findings in court. Forensic expert reports of cases thus may be supported by the visualizations from the presented software framework, and may improve the overall impression judges and jurors develop of a case during trials.

Two ways to produce 3D DRMM's for presentation purpose were found to be feasible, while the use of MR whole-body scans does not seem to be suited for this purpose due to technical limitations, the high effort, and the fact that patients larger than 1.85m are problematic to scan. Generic anonymous models are useful for case preparation, since no additional effort of a victim is required. The lack of accuracy of such generic models may be tackled by using a database of models with different age, height, sex, and body composition. From this database slight adjustments of a model are possible to improve patient resemblance. However, it has to be stressed that shape and size of injuries might slightly vary when visualized using a generic DRMM. It is not possible to exactly reproduce such injuries, and no measurements should be made from these visualizations. A provided additional injury macro photograph including scale is the appropriate tool for measurements and may be included into a visualization (see Fig. 10b,c and 11b).

With little effort for the victim and the forensic expert, the method using the Kinect based structured light reconstruction allows a patient-specific model generation. In this case anonymization is very likely to be required. The question whether the generic model is superior to the more realistic 3D reconstruction due to its higher level of abstraction is an important issue for forensic experts, since an objective view of a case is indispensable. Showing too much personal details might thus be counterproductive. From our experiments concerning the accuracy of the Kinect based 3D models, we conclude that an external calibration is necessary. This is in accordance with related studies, although we did not see as large errors for our test object as were reported in these studies. A low-cost setup in a similar price range further improving accuracy could be set up using a digital SLR and software like Agisoft PhotoScan. However, we found the Kinect setup more manageable and simpler to use compared to this multi-view stereo setup, with the accuracy of the Kinect setup being sufficient for our visualization purpose.

Our current Kinect based patient specific reconstruction setup also shows some limitations. First, it is crucial that patients hold still during the scan. Optimally, the Kinect scan takes place in the same position as the MRI scan. If this is not possible, small posture adaptations are required to match 3D model and MRI scan. Further, there is no photogrammetric reference coordinate system, that would allow the automatic mapping of photographs onto the surface, this step has to be performed with additional markers or manually. As a consequence we currently do not propose the Kinect setup for digital documentation of injuries with the goal of measuring injury sizes from the 3D model, but solely to provide an overview of injuries to support in-court presentations, which – similar to the generic 3D DRMM – should be assisted by macro photographs involving a scale. If more

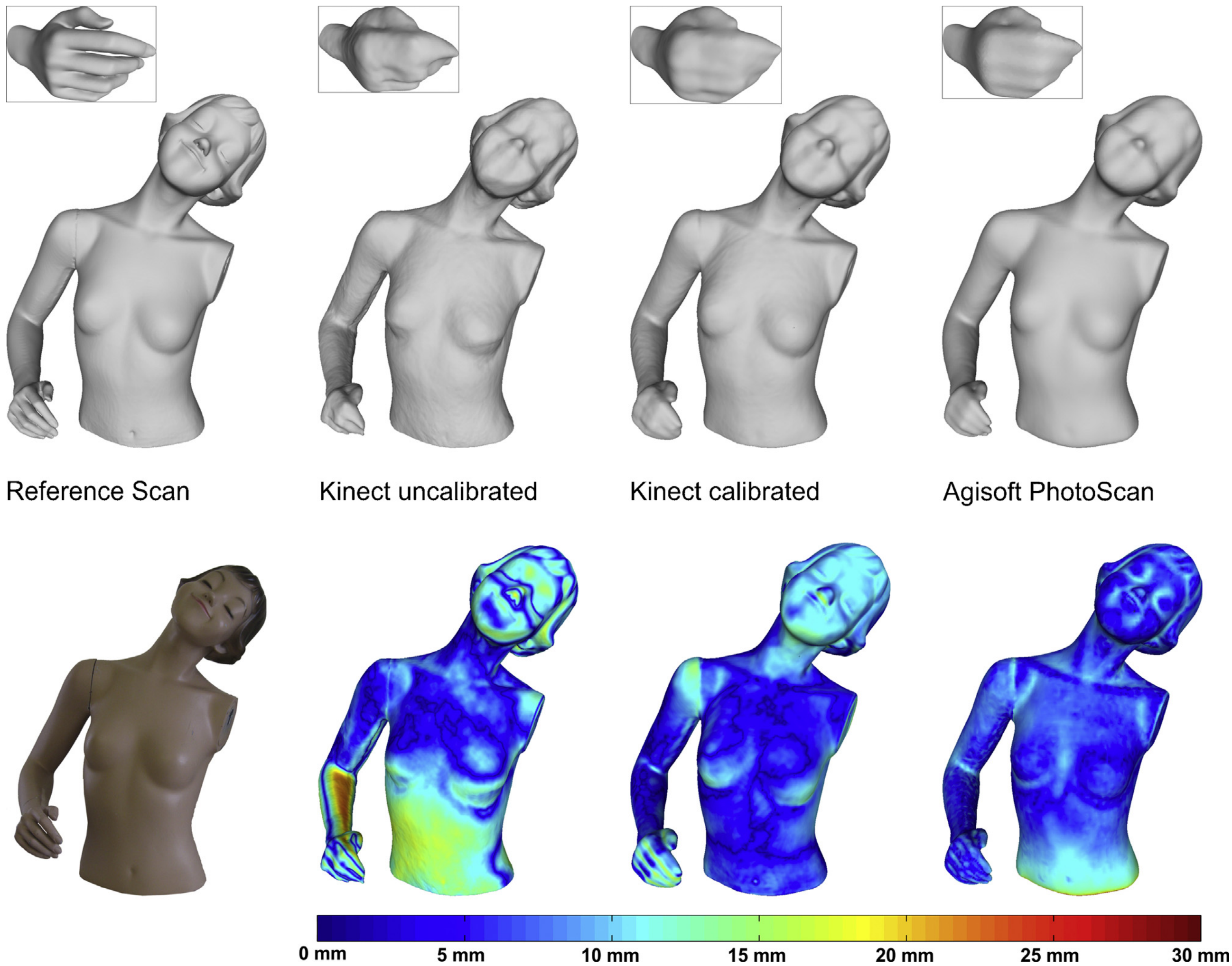

Fig. 12. Qualitative results of the experimental evaluation of the accuracy of patient-specific model reconstruction compared to a reference scan based on structured light. Top row shows the reference scan and three variants of low-cost setups performing the reconstruction of a display dummy test object. Zoom in on the hand is available. Bottom row shows the original display dummy and the color-coded difference visualizations of the low-cost 3D models compared to the reference scan. Color code maps warmer colors to higher errors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

accurate true-to-scale and -color 3D documentation is required, that directly allows metric measurements, then a more complex photogrammetric setup needs to be used [11].

The presented software work-flow proved to be suitable for the purpose of forensic case preparation. The various intermediate registration steps to combine forensic data with the 3D DRMM are the most important prerequisites. Registration accuracy of the marker based 3D–3D and 2D–3D registration has been evaluated and found sufficient, detailed results on registration accuracy can be found in the master thesis of Höller [30].

Concerning the effort for preparing cases, a distinction has to be made between using patient-specific or generic DRMMs. In the latter case, a forensic expert together with a forensically educated radiology technician require around 30 min for the preparation including registration and manual intervention. If a patient-specific model based on structured light is needed, this time currently increases by 1 hour of preparation, due to taking the 3D scan on a turntable, which takes a few minutes, and requiring some post-processing steps. We expect that by further automating these steps, this effort can be decreased to around 30 min to 1 h total. A limitation of our current DRMM concept is that large adaptations of posture between the injuries and the 3D model need to be avoided, since our simple kinematics based on the skeleton and associated skin weights is not robust to large posture changes, thus deforming the models unrealistically.

In the two presented case studies externally visible findings as well as internal injuries found in different radiological modalities are displayed in a single 3D reference model. In the first case (Section 2.3.1) only external injuries were found, however, involving different areas at the front and at the back of the body. This distribution makes it difficult to imagine the context between the single injuries, and to derive an intuitive perception between the single events and the findings caused by them. In this case the impacts and the thus originating injuries can be nicely combined: the hits in the face and on the upper body caused corresponding bruises on the forehead and on the lower lip as well as on the breast and the clavicle region, and the reddening of the skin on the neck was consistent with strangulation. From the visualization the victims version of the sequence of events was found to be plausible.

In the second case (Section 2.3.2) numerous and mostly internal injuries were found. In such cases, an overview of findings is particularly of interest. The jury members are not educated in anatomy, however, they need a presentation of the distribution of the injuries and the forces which must have been applied to cause them. In this case it could be shown how the head must have suffered massive blunt trauma, as there were lesions at the back of the head and a corresponding contre-coup lesion in the front part of the brain. Internal injuries can not be displayed on photographs and radiological data are hard to understand for medical laypersons. Thus, the visualization in a single context such as the proposed 3D reference models is a major contribution to an efficient and comprehensive understanding of complex injury systems in court.

5. Conclusion and outlook

A work-flow was proposed to create a 3D reference model which allows the placing of diverse forensic findings in a common, visually defined coordinate system. This enables an improved, intuitive understanding of forensic findings in court. A second application, where the necessity for such a reference model arises, is the comparison of internal and external injuries in the context of validation studies. We will investigate the suitability of our models for this comparison as well as the use of our models for deceased victims in future work. Whether forensic experts and jurists prefer the use of patient-specific or generic, abstract models is an important issue, which will be investigated in an upcoming study. Both kinds of DRMM have their specific advantages, and with the presented reconstruction method based on the Kinect device, widespread use of patient specific models is possible, thus enabling the forensic expert to select the most appropriate model on a per-case basis. However, it needs to be stressed that no measurements should be made from the 3D DRMMs and photographs providing scale of injuries are required to be shown in court additionally. Open questions that remain for future research are how to embed our 3D DRMMs into a photogrammetrically consistent reference coordinate system to enable documentation of injuries that contains measurable structures. Also the problem of larger deformations due to different patient postures and their solution in terms of accurate skeleton fitting and linearly blending the skin poses an interesting research question.

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