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Technical Note

Using virtual reality for forensic examinations of injuries

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ABSTRACT

The ability to accurately determine injury dimensions is an essential property of forensic documentation. The current standard for injury documentation is photography using a scale to approximate the injury dimensions in the image. The technical qualities of the photograph, such as orthogonality, depth of the field and sharpness of the desired area, are vital to obtaining a correct measurement. Adequate training of the forensic staff can reduce technical errors; nonetheless, there will always be some loss of information when visualizing an injury as a three-dimensional (3D) object on a two-dimensional (2D) photograph.

The shortcomings of 2D photographs can be resolved by using 3D photogrammetry, which allows 3D documentation of persons and their injuries. A series of photographs has to be acquired and processed in photogrammetric software to create a photorealistic 3D model.

In a prior study, a mannequin equipped with wound tattoos of known dimensions was documented with 3D photogrammetry using a multi-camera device. On the created 3D model, the dimensions of the injuries were then measured and compared to the dimensions approximated from standard forensic photographs. The results showed that the photogrammetric measurements in 3D are more accurate than the approximations performed with standard forensic photographs. In this subsequent study, the created 3D model was visualized and surveyed in virtual reality (VR), and the results were compared to the previous study. Our goal was to establish how accurately injuries can be measured in VR compared to the standard forensic photo documentation and photogrammetric method that is used on computer screens. We found that the measurements in VR are more accurate than the approximations from forensic photo documentation, but slightly less accurate than the photogrammetric measurements performed on a computer screen in dedicated software.

In conclusion, photogrammetric software and virtual reality tools can both be used to make accurate size measurements of forensics-relevant injuries. Furthermore, 3D models can be visualized in varying ways allowing a much better understanding and review of injuries, even after the injury has healed.

1. Introduction

An important part of forensic investigations is documentation. This includes written documentation of statements, as well as photographic documentation of evidence [1]. The documentation procedure is often standardized and can include specific notes, such as a time stamp or the location [1]. This documentation procedure is also important during forensic medical examinations of people; specifically, photographic documentation has a high importance [1,2]. The gold standard for the forensic documentation of injuries is that all injuries are drawn on a body diagram, documented in written form and visually displayed with a photograph [1,3]. The photo documentation is vital for an objectively correct representation of the injury for subsequent examinations [1]. The technical qualities of the photograph are important to ensure clear interpretation of the injuries. Factors such as orthogonality, depth of the field and sharpness of the desired area, as well as the requirement to take a coherent series of images, including an overview image and detailed view of the injury, are necessary for a good judgement of the injury [1,2]. Due to its complex technical requirements, an experienced forensic staff is required to acquire the photographs. Adequate training of the forensic staff can reduce technical errors; nonetheless, there will always be some loss of information when visualizing a three-dimensional injury in a two-dimensional photograph [1,2]. This is especially true when the approximation of the injury dimensions using a scale bar depends highly on the correct depth placement of the scale in the image [1].

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To overcome these shortcomings of 2D photographs, 3D photogrammetry can be used. Photogrammetry is a technology which allows 3D documentation of objects, scenes and persons. These 3D models can be used to reconstruct crime scenes, including location, objects and persons, or in forensic medicine to match injuries with an injury causing object [2,4–8]. To create a photogrammetric 3D model, a series of overlapping images from different angles have to be acquired and digitally processed into a photorealistic and scaled 3D model [4]. Photogrammetry is routinely used in the forensic surface documentation of injuries [1,2].

In forensic medicine, this photogrammetric procedure can be performed manually or with multi-camera systems, such as the "Photobox" Botscan by Botspot. This device documents the whole body surface with multiple cameras, which record simultaneously [9]. Because it only takes a fraction of a second to record the image, and due to the cameras being in a stable and adjusted system, this process requires less time than taking photographs with a handheld camera and reduces issues with object motion. After post processing the images, the created, fully textured 3D model gives a good overview of all body parts. Areas of interest can be zoomed in on, and injuries can be looked at in detail at any time. However, the person being examined has to be able to stand in an upright position without assistance in order to perform the Photobox scanning procedure [9]. Overall, the Photobox allows a quick recording of a whole body that can then be transformed in a 3D model [9]. Photogrammetry allows a better reconstruction and visualization of injuries than the standard forensic photography procedure [5,8,10,11].

A major problem of the 3D models is that looking at them on a 2D hardcopy or screen reduces the 3D information to 2D, consequently losing the depth information. Hence, 3D visualization technologies are required to provide analysis of the injuries in 3D. One technique for 3D visualization are 3D virtual reality head mounted displays (HMDs) [12]. Virtual reality (VR) is a technology that allows the user to observe and interact with a virtual 3D environment. The interaction in VR can vary from looking around the scene to interactively modifying the environment [13,14].

In forensics, VR has been used to document and reconstruct crime scenes and traffic accidents [12].

In the field of forensic injury documentation and visualization, VR has not yet been introduced. In this article, we evaluate whether injuries can be examined in VR, based on measurements of the injury dimensions, by comparing them to the standard method of measuring using photos, as described in Grassberger et al. [1].

2. Materials and methods

In this section we will explain how 3D data acquired with the Photobox is visualized in VR and how injury measurements are performed.

2.1. Set of data

Michienzi et al. [11] investigated the accuracy of photogrammetric measurements using a 3D model of a mannequin. In our study we used the 3D model created by Michienzi et al. to perform our measurements and allow for direct comparison to their article.

In the study by Michienzi et al., a mannequin was equipped with 43 wound tattoos on all extremities, the torso and the head. Before attachment to the mannequin, the flat tattoos were measured to the maximum extent of the injuries presented on the sticker, as well as to predefined points marked clearly on the tattoo. These measurements on the flat tattoos present the reference measurements of the highest quality and were used for subsequent evaluation of the measurements that were performed in VR.

Parameters for 3D reconstruction and photo documentation can be found in Michienzi et al. The injuries were documented in both ways, standard forensic photography and 3D photogrammetry. For the standard documentation, a single hand-held camera was used, and the dimensions of the injuries were approximated based on a scale bar positioned in the image [11]. The 70 photogrammetric images that were acquired with the multi-camera device Botscan by Botspot [9], each with a resolution of 5184 × 3456 pixels, were used to create a 3D model using the Agisoft PhotoScan Professional software. For the creation of the 3D model, the software was set to the high-accuracy camera alignment, with high quality selected for the dense point cloud, as well as a high number of triangles for the 3D surface mesh. The texture was created with 16384 × 16384 pixels to allow for high quality representation of the injuries on the 3D surface. All injuries were then measured on the 3D model in Agisoft Professional.

2.2. Preparation

To measure the injuries in VR, we had to visualize the 3D model in a virtual reality scene. We exported the 3D model from Agisoft PhotoScan Professional (Version 1.2.3.2331, Copyright © 2015, Agisoft LLC, Saint-Petersburg, Russian Federation) into the Wavefront .obj file format [15]. Photogrammetric documentation of an object produces a set of 3D coordinates referred to as a point cloud [4]. Forming polygons between these points produces a mesh that approximates the shape of the object. We exported the mesh of our 3D model from Agisoft as an .obj file. The materials were defined in the material template library (as an .mtl file) and only referenced the texture file of the 3D model, which was exported as a .jpg file. These 3 files were then imported into the Unity software (Version 2017.3.0f3 © 2017 Unity Technologies ApS, San Francisco (CA), USA) to visualize as a 3D model.

Comparing the texture of the 3D model in VR to the texture visible in Agisoft, we found that the resolution of the injuries was much lower in VR. This difference was caused by the version of Unity used, which currently allows a texture of only 4096 × 4096 pixels per object. Thus, we edited the 3D model in Agisoft and segmented the 3D model in 5 parts (lower leg, upper leg, abdomen, thorax and shoulder/head). The distribution of the injury tattoos on the mannequin lead to some difficulties segmenting the 3D model. We could not cut through injuries because Agisoft was not able to create faultless textures for parts with split injuries on the edges. Because we also performed the segmentation manually in Agisoft, it was necessary to have overlapping parts with no split injuries on the edges. A texture of 4096 × 4096 pixels was created for each of the parts. Then, all the parts were reassembled to a complete model in Unity, resulting in a second model with higher overall texture resolution than the previously imported model (Fig. 1). The two models were differentiated as low-resolution and high-resolution models (Fig. 2A and B).

The visualization in VR for the head mounted display (HMD) was performed in Unity using SteamVR (Version 1.2.3, Valve Corporation, Bellevue (WA), USA). SteamVR provides tools to visualize the VR scene on the HMD and create a player in the scene. The HMD we used was the HTC Vive (HTC, Taoyuan, Taiwan) with two controllers. The controllers can be used to perform actions by clicking on different buttons. Another SteamVR functionality we used was a horizontal teleporting function to move around the scene.

We added some missing functionality by writing additional scripts in C#. The following tools were implemented:

1. A tool for measuring distances in a 3D space.
2. A tool for creating screenshots.
3. A tool to scale and elevate the player.

To use the distance measuring tool, we implemented a tool in Unity to mark points in space. A function was implemented that calculated the distance between two marked points. When marking points in sequence, the distance between the points was calculated in a straight line. In body areas with bent surfaces, the injuries can be measured with multiple points in sequence to approximate the injury curvature and make the measurement more accurate. Unity then sums up all the fractions to the total dimension of the injury. After completion of a measurement, the measured distance is displayed next to the controller (Fig. 3).

We created a screenshot function to document the measurements and take pictures of the injuries. Without manipulation in VR, the model appeared to be the same size as in real life when in front of it.

To be able to view the injuries in detail, a scaling function was implemented. However, scaling the 3D model would lead to a change in dimension of the injuries, which would falsify the measurements. Therefore, we decided to implement the scaling function on the player's size rather than on the 3D model's size. When downscaling the player in size, the surrounding scene seems larger to the HMD operator. Because the coordinates of the 3D model stay the same in this case, the measurements are still true to scale. Furthermore, physiologically, the upper extremities have a slight tremor [16]. This leads to vibrations of the controller in the scene, causing inaccuracies when marking points in the 3D space. A technical way to reduce these inaccuracies is by scaling the operator to a smaller size, which minimizes the vibrations relative to the scene. However, when the player's size was scaled to down, it was impossible for the operator to see all the injuries from the ground of the scene. Thus, a vertical teleporting function was added to hop to different heights in the scene, making it possible to view every injury.

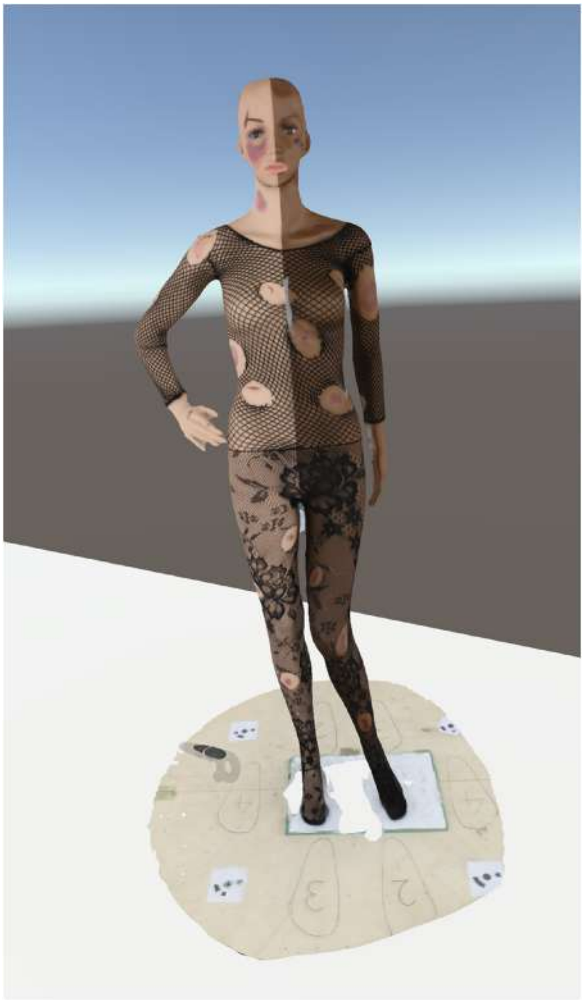

Fig. 1. The low-resolution 3D model in the virtual reality scene, viewed with the HTC Vive.

2.3. Measurements

Three different measurements were conducted in VR by a medical student. Both the low- and high-resolution models were included in the measurements. In the first attempt, the low-resolution model was measured without scaling the operator, so that the injuries appeared the same size as they would in reality. For the low-resolution mannequin, this was sufficient as the texture did not provide any more detail. The model with the higher resolution was then measured using the scaling function; therefore, the injuries appeared larger and it was possible to examine them in more detail and differentiate an injury from the surrounding skin.

The third measurement was performed on the high-resolution model but without using the scaling tool. However, the third measurement was not evaluated, due to a lack of practical relevance. In a real-life scenario, either fast low-resolution models are used, or accurate measurements with scaling will be performed on high-resolution models.

Measurements were made on the maximum extent of the injuries, which had to be estimated by the operator. In addition, point-to-point measurements of length and width were made using the well-defined spots on the tattoos.

2.4. Statistical analysis

The absolute and relative discrepancies and the standard deviations of all measurements were determined using the reference injury measurements made on the flat wound tattoos. The Shapiro–Wilk test was applied to determine the normal distribution of the data. The discrepancies between reference and VR measurements were compared to the forensic photo documentation and to the photogrammetric measurements made by Michienzi et al. A Wilcoxon test was performed to test the significance of the difference between the VR measuring techniques and the reference measurements [17]. Finally, a Bland–Altman plot was created to visualize the agreement between the VR measurements and the forensic photo documentation [18]. The data analysis was conducted in Microsoft Excel (Version 14.0.7208.5000 © 2010 Microsoft Corporation, Redmond (WA), USA) and IBM SPSS Statistics for Mac (Version 25.0 © 2017 IBM Corporation, Armonk (NY), USA).

3. Results

To compare the VR measurements to the forensic and photogrammetrical measurements, our data was assessed by the mean, standard deviation and a 95% confidence interval. The mean discrepancy to the reference measurements was calculated in mm and is also relative to the reference extent of the injury.

The mean discrepancy of the measurements in defined dimensions was higher in the low-resolution VR model (5.2%–9.1%, Table 1) compared to the high-resolution VR model (3.9%–4.4%, Table 2). Due to a lack of definition in the maximal extent of the injury, there were very large differences between the measured maximal extents and the reference measurements of Michienzi et al. We decided that if the measured distance of an injury was more than twice the size of the reference measurement, then the measurement would be considered false and excluded from the

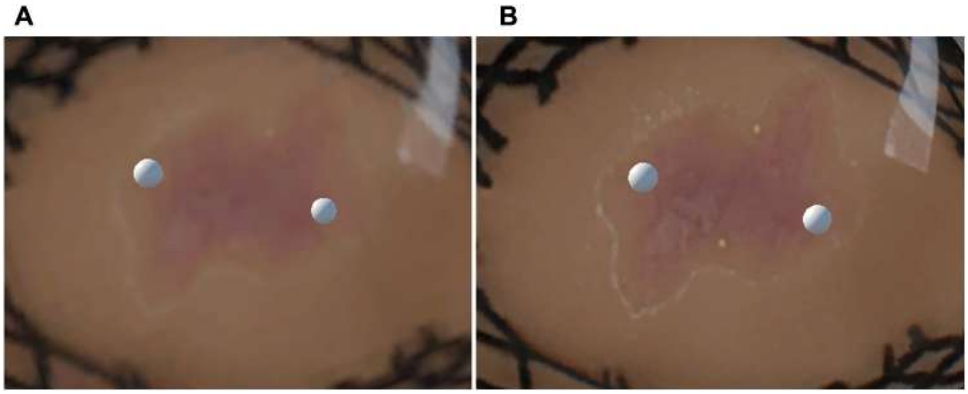

Fig. 2. There is a visible difference of resolution between the low-resolution model (Fig. 2A) and the high-resolution model (Fig. 2B), exemplified with an injury tattoo on the hip region of the model. The marks are 3D spheres added in VR on the model and show that the resolution is a limitation of the texture of the model and not a limitation of the rendering.

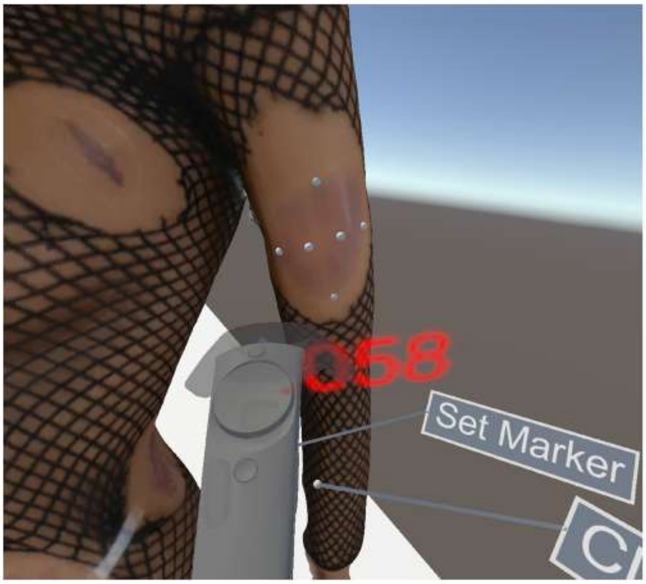

Fig. 3. After completion of a measurement in the VR scene, the calculated distance (in metres) is displayed next to the controller.

study. Measurements in defined extents were not affected. After exclusion of the outliers, the number of injuries included in the calculations ranged between 27 and 42. For the maximal injury extent, the mean discrepancies then ranged between 7.8% and 18% (Tables 1 and 2). Due to the lack of definition of the maximal extent of the injury, it was decided to not further evaluate the maximal extent measurements. For further comparison, we then only used the point-to-point measurements, as they are well defined and do not provide human error by guessing the injury extent. Michienzi et al. measured point-to-point dimensions both with forensic and photogrammetrical techniques. They found out that the mean discrepancies to the reference measurements ranged from 8.4%–11.1% for the forensic technique and 3.4% in both length and width for the photogrammetrical technique. As shown in Tables 1 and 2, the VR point-to-point measurements, both with lower and higher resolution, have smaller mean discrepancies than the forensic measurements obtained by Michienzi et al. but larger mean discrepancies than the photogrammetrical measurements [11]. Thus, both VR measurement techniques are more accurate than the forensic measurements, but less accurate than the photogrammetrical measurements made on a computer screen.

A Bland–Altman plot was created to assess the agreement of the two measurement techniques. To this end, data acquired by Michienzi et al. was compared to measurements made in this study. The point-to-point measurements were used to compare the reference measurements to the forensic measurements and to the high-resolution VR measurements (Figs. 4 and 5). The high-resolution VR measurements were then also compared to the forensic measurements (Fig. 6). For a better comparison, point-to-point measurements of both length and width were grouped together for each measurement technique. The X-axis of the Bland-Altman plot shows the mean value of a certain injury dimension obtained by the two measurement techniques that are being compared. The Y-axis shows the difference between the two measurements. The drawn line in the diagram represents the mean discrepancy of all measurements, and the dashed lines represent the 95% confidence interval. Comparing the high-resolution VR measurements to the forensic measurements, the VR measurements are closer to the reference measurements, with a mean discrepancy of 0.69 mm compared to 2.75 mm obtained by the forensic method. The standard deviation of the high-resolution VR measurements is smaller than the standard deviation of the forensic measurements (1.37 mm compared to 2.84 mm). Figs. 4 and 6 confirm the assumption of the 95% confidence interval with 4 points (n = 81 and n = 80, respectively) lying outside the 95% confidence interval, whereas in Fig. 6, there are 6 points (n = 80) lying outside the assumed 95% confidence interval.

All Bland–Altman diagrams show a regular distribution of dots on the X-axis, which indicates a wide variety of injury sizes used in the test. Fig. 4 (forensic vs. reference) shows larger discrepancies

Table 1
Differences in wound sizes measured on the low-resolution VR model and reference wound sizes.

	Maximal length	Maximal width	Defined length	Defined width
N	40	29	42	38
Mean discrepancy	3.6 mm (9.3%)	3.2 mm (16.0%)	1.8 mm (5.2%)	1.9 mm (9.1%)
Standard deviation	3.5 mm	3.3 mm	1.5 mm	1.9 mm

Table 2
Differences in wound sizes measured on the high-resolution VR model and reference wound sizes.

	Maximal length	Maximal width	Defined length	Defined width
N	40	27	42	38
Mean discrepancy	2.7 mm (7.8%)	3.3 mm (18.0%)	1.7 mm (3.9%)	0.9 mm (4.4%)
Standard deviation	2.5 mm	2.8 mm	1.2 mm	0.9 mm

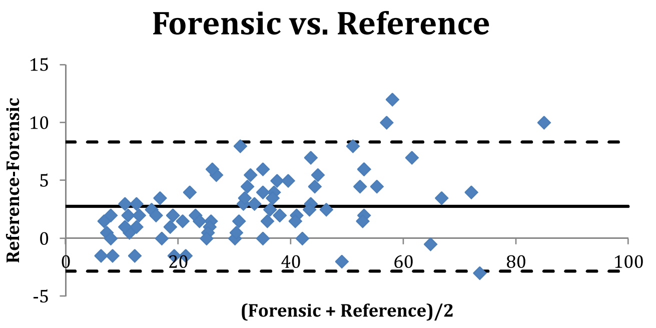

Fig. 4. Bland-Altman plot of the forensic measurements compared to the reference measurements.

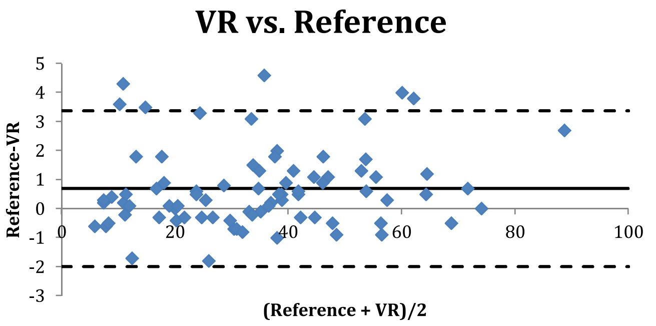

Fig. 5. Bland–Altman plot of the high-resolution VR measurements compared to the reference measurements.

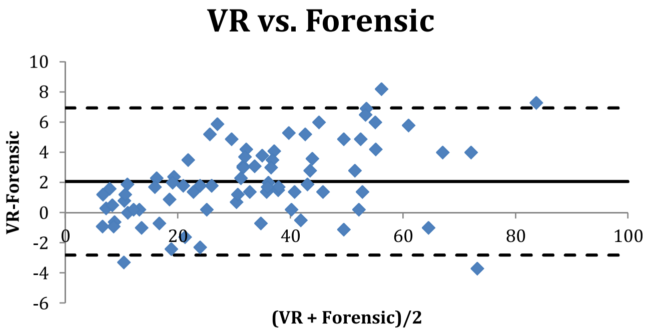

Fig. 6. Bland–Altman plot of the high-resolution VR measurements compared to the forensic measurements.

with increasing injury sizes, whereas Fig. 5 (VR vs. reference) shows that the discrepancies are evenly distributed on the X-axis. Thus, the injury size does not influence the accuracy of the high-resolution VR measurements, whereas the forensic measurements are more precise with smaller injury sizes.

A Shapiro–Wilk test of the mean discrepancies showed no normal distribution for all measurements ($p < 0.05$). The Wilcoxon tests of both low- and high-resolution point-to-point measurements to the reference measurement showed a significant difference ($p < 0.05$). However, the Wilcoxon test between the low- and the high-resolution point-to-point measurements showed a p-value of 0.192; therefore, the test shows no significant difference between the two VR measurement techniques.

4. Discussion

Our goal in this article was to evaluate whether injuries documented using photogrammetry can be examined and measured accurately in VR. Low- and high-resolution VR measurements were compared to forensic and photogrammetrical measurements obtained by Michienzi et al. Using Bland–Altman plots, we compared the high-resolution VR measurements and the forensic measurements to the reference measurements. If two measurement techniques are comparable, both the standard deviation and mean discrepancy should be small [18]. With smaller mean discrepancies and smaller standard deviations, we found that the high-resolution VR measurements are closer and more comparable to the reference measurements than the forensic measurements. Mean discrepancies show that both low- and high-resolution VR measurements are more accurate than the conventional forensic measurements, but less accurate than the photogrammetrical measurements.

Photogrammetrical injury documentation has been found as an accurate alternative to forensic injury documentation that uses a single hand-held camera [5,8,10,11]. Measurements in VR turned out to be less accurate than photogrammetric measurements. However, the operator receives more spatial information when looking at the injuries in a virtual space compared to looking at the injuries on a 2D screen. Further research needs to be conducted to determine to what extent this might influence the operator's judgement and interpretation of an injury.

To reach the same level of accuracy as the forensic measurements obtained by Michienzi et al., it was sufficient to measure the injuries using the low-resolution VR model. By increasing the texture resolution, we managed to increase the accuracy of the measurements. However, creating the low-resolution 3D model with a single 4096 × 4096 pixel texture required considerably less time than the high-resolution 3D model and; therefore, this process be easier to integrate into the workflow of forensic injury documentation.

We found that it is difficult to assess the maximal injury dimension. Due to the lack of a proper definition, experimenters chose different orientations for determining length and width and disagreed on where the injuries started and ended. This disagreement made the comparison of maximal injury sizes to the reference measurements impossible.

In body areas with curved surfaces, multiple points in sequence had to be marked to approximate the injury curvature. The distance between each mark was then summed up to a total dimension of the injury. Using the scaling function could reduce vibrations of the controller relative to the scene. Nevertheless, approximating the injury curvature always leads to some inaccuracies in the wound dimension. It might therefore be useful to have a VR function that allows measuring the shortest distance between two points along the mesh of a 3D model. This process could reduce the amount of time needed for measurements on bent surfaces and make the measurements more accurate, thereby requiring the operator to only mark a starting and ending point for the measurements. This process could be improved further by an algorithm detecting the injury automatically or semi-automatically, thereby requiring even less input by the operator.

In future studies, it might be beneficial to test measurements in VR on 3D models of real people. Compared to the injury tattoos on our mannequin, real injuries have more complex surface structures. Therefore, the measurement of real people in VR might differ from the measurement of a mannequin.

5. Conclusion

VR using a low-cost HMD is a suitable tool for the 3D documentation and measurement of forensics-relevant injuries.

Conflicts of interest

None.

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