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Authors: Fahrni S, Delémont O, Campana L, Grabherr S

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Corresponding Author:	Stella Fahrni, MSc Ecole des Sciences Criminelles Lausanne, Vaud SWITZERLAND
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Ecole des Sciences Criminelles
Corresponding Author's Secondary Institution:	
First Author:	Stella Fahrni, MSc
First Author Secondary Information:	
Order of Authors:	Stella Fahrni, MSc
	Olivier Delémont, Professor
	Lorenzo Campana, Dipl.-Ing
	Silke Grabherr, Professor
Order of Authors Secondary Information:	
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Keywords

forensic imaging; 3D modelling; methodology; ACE-V; analysis.

Introduction

During the last decade of the 20th century, the improvement of digital photography [1,2] and imaging techniques enabled the proliferation of solutions to record 3D data through the use of digital photogrammetry and lasergrammetry [3-7]. In legal medicine, especially in forensic traumatology, another alternative of optical scanning device, mainly known as 3D surface scanning, was then put forward for the three-dimensional analysis of the volumetric adequacy of a wound and a possible injury-causing instrument [8]. The contribution of 3D surface scanning instrumentation was mainly emphasised through specific applications, mostly in combination with other non-invasive imaging techniques such as MDCT (multi-detector computed tomography) [9-13] or MRI (magnetic resonance imaging) [10,12,13]. These specific applications were shown by case examples, mostly cases of traffic accident reconstructions [4,5], comparisons of wounds with the injury-causing instrument [3,14,15,6,16,7], and event scenario assessments [4,5]. Several related case reports praised the high quality of the images and other general advantages of the 3D surface scanning techniques, such as an objective and non-invasive 3D documentation, the high resolution and the accuracy [4,17,8].

In the existing literature, no detailed information is provided about parameters and conditions of application of the 3D scanning techniques. Using 3D data remains a mostly veiled and implicit process: the methodological framework for the performed analysis, especially considering the volumetric comparison of the sets of 3D data, is rarely explained, if not undefined. It generally relies on the superimposition of 3D models generated from the surface scanning data of the mark (the wound) and of the suspected injury-causing instrument. The discussion of the results of this superimposition and their meaning are in most cases not emphasised. Generally, the methodological approach for the implementation of the technique, its deployment in the multidisciplinary and collaborative process of (criminal) event reconstruction, and the scientific justification of the conclusions drawn from the application of the 3D imaging techniques are not explicitly considered. Examining the pertaining literature, we observe an over-representation of case reports, yet convincing, and only a very small number of systematic and rigorous basic research studies [18,19].

The present study was focussed on the use of 3D surface scanning technique for the general process of comparison between a mark – representing a wound – and an object. In some other fields in forensic science, a methodological approach, called ACE-V (Analysis, Comparison, Evaluation and Verification), is used for the study and comparison of traces [20,21]. The procedure followed in our study was inspired by this ACE-V process. We did not claim to setup a complete and systematic study, but to implement an experimental design that could unveil the pitfalls of a subjective comparison made from 3D data. The purpose was to explore the ability of an operator, by means of 3D surface scanning, to take a decision on the association/exclusion of an incriminated tool as the source of a mock wound. Ideally, the operator was told to try to attribute the mark to one specific object. On the basis of the results of this exploratory set of experiments, we tried to delineate a possible methodology that could overcome the highlighted limitations. To our point of view, such a methodology should encompass several sequential steps that should be clearly defined and formalised, following the ACE-V approach: the description of wound, the analysis of its informational content, the comparison with a reference trace made by an instrument, and the assessment of the value of this comparison.

Material and Methods

This study was divided in sequential steps: an initial phase of analysis was undertaken separately for each trace and each object. It was followed by a qualitative comparison taking into account the general features observed during the analytical phase and the superimposition of the 3D models of the traces and the objects. Finally, a quantitative step was carried out by comparing pairs of measurements between a mark and an object.

Specimens' preparation

We composed a set of blunt instruments by collecting 15 household tools, rigid objects easily accessible in daily life or able to cause blunt injuries: pliers, black wrench, silver wrench, monkey wrench, shower head, chair leg, hammer, axe, poker, jack handle, carpenter hammer, vise-grips, sledge hammer, file, bat.

Twenty-three marks, referred as 'mock wounds', were produced by seven different persons striking the surface of watermelons (average length between 20 and 25 cm and average diameter of approximately 20 cm) with the fifteen instruments, at least one and maximum twice per tool. This way of wound production was chosen because it results in a realistic blunt force trauma pattern, and that it was not aimed to compare wounds with each other. On each watermelon, three or four wounds were made, using two or three tools. Each watermelon, each wound as well as each tool was individually labelled. After the production of a mock wound, the person that produced it, filled in a so-called 'lesion protocol' with all the details related to the tool used and conditions of mark production. The seven volunteers who hit the watermelons were 3 women and 4 men aged between 29 and 64 years old. No specific rules were given to them, just to strike the watermelons as they would hurt somebody. This phase took place indoor, in the autopsy room. The main researcher in charge of the study did not take part to this production phase of mock wounds, nor was she informed about which tool was used to produce each of the marks.

3D data acquisition: from scanning to modelling

3D surface measurement was processed through a non-contact optical 3D digitising system Gom ATOS Compact Scan 5M (Gom, Braunschweig, Germany)(Figure 1), which allows to obtain 3D models from real data with high resolution and accuracy. The functioning of this scanner relies on the fringe pattern projection (blue light) of adapting array of stripes that impact the surface to be measured. Two 5-million-pixels cameras record the deflections of the stripes induced on the shape of the surface. By triangulation principle, the measurements from both cameras are merged in a point cloud representing the surface, with high resolution and accuracy. [22,23]. Acquisition was controlled through the ATOS Professional V7.5 SR2 software package, also used for some further treatments in conjunction with a 3ds Max 2013 software. Two different measuring volumes (MV) – corresponding to different pairs of camera lenses – were used on the scanner depending on the size of the object: MV 150 (resolution up to 0.062 mm) and MV 300 (resolution up to 0.124 mm). This required in accordance the use of two different calibration panels: CP40/MV170 and CP40/MV320.

Figure 1 – Gom ATOS Compact Scan 5M

A calibration of the scanner was regularly carried out during the period of scanning, and in particular every time the measuring volume was changed in order to assure minimal deviation in measurements. Markers were placed around the mock wounds, on the surfaces of the tools as well as on the support of the tools. Mock wounds and tools were scanned in a room at ambient temperature (around 21°C) under controlled and stable luminosity. Parasite movements were reduced to a minimum level by fixing the different parts of the camera to a tripod and by working in an isolated room. Objects whose surfaces were too shiny or dark were first sprayed with a solution of titanium dioxide (TiO_2) powder in ethanol, to reduce gloss and prevent the production of artefacts.

Tool scanning was performed in a two-step process: the front side was first digitised, then the object was turned over on the support and the back was scanned. Marks on watermelons did not need such a process as they were situated only on one side of the fruits. Each watermelon was scanned with the MV300 measuring volume (300 x 230 x 230 mm), as the majority of the tools (Figure 2). For some smaller objects, the MV150 measuring volume (150 x 110 x 110 mm) was preferred. A complete operation of 3D data acquisition for a mock wound required an average of 15 to 30 minutes, and 30 minutes to more than one hour per tool depending on the complexity of the surface. Watermelons were scanned within one to four days after the production of the mock wounds, following availability of the instrumentation and of the autopsy room. Watermelons were kept in a fridge between the production of the wound and the scanning process.

The points corresponding to the support of the objects were erased from the 3D scans using the Gom ATOS software. Both faces of the tools were merged together and 3D models were created from the point clouds by polygon meshing with as many details as possible (Figure 3). No further treatment was processed on these 3D models (for instance, no automatic filling of some holes on the surface of the model).

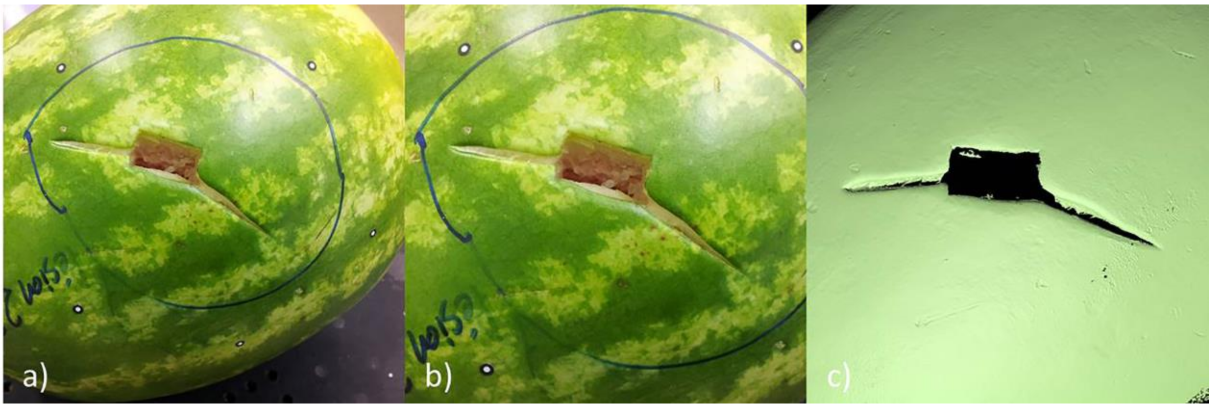

Figure 2 - Example of a scanned lesion. a)-b) Photographs of lesion 23 on the watermelon; c) 3D model of lesion 23 obtained from the GOM scanner

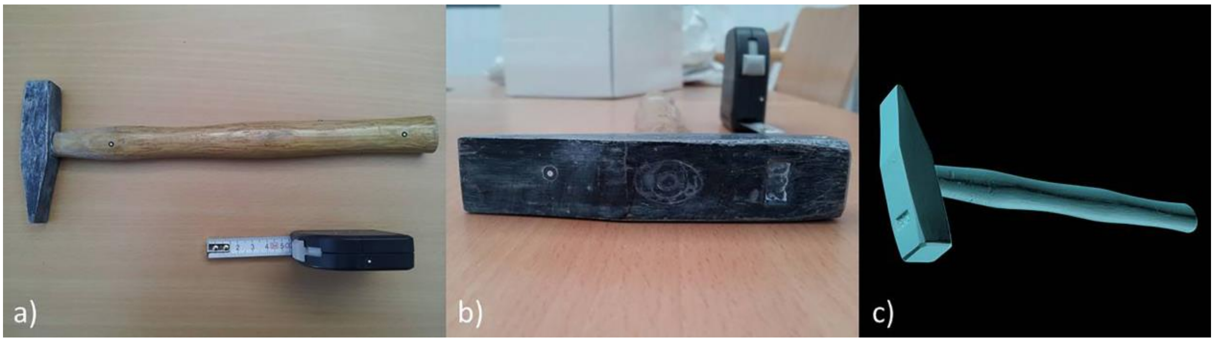

Figure 3 - Example of a scanned object. a)-b) Photographs of the hammer; c) 3D model of the hammer obtained from the GOM scanner

Qualitative analysis and comparison

The 3D models of each mock wound and each tool were separately scrutinised by means of the 3DS Max® software (edition 2014, Autodesk). During this phase of *analysis*, each mark was examined by the main operator; the type and location of the visible characteristics were assessed enabling to evaluate the confidence on the outcome of a comparison process. In this perspective, the quality and quantity of information present and useful for a comparison process were systematically considered and annotated. For every mark, general features, such as shape and dimensions, and more specific characteristics (patterns, particularities, etc.) were compiled. When possible, the direction of production of the mark was also considered. From these elements, the marks were distributed into three categories according to the type and quality of information extracted:

- Type I: Clear general pattern with high degree of specificity;
- Type II: General pattern not clearly printed or with low specificity;
- Type III: No distinguishable general pattern or high destruction of the surface.

This analysis step was also undertaken by the main operator on every tool, gathering information about the general features and measurable characteristics on each one of them.

Then, a *qualitative comparison* took place for each trace, taking sequentially into account each of the considered tools. This qualitative approach included two dimensions: 1) the direct comparison of the general features and particularities observed during the analysis phase, and 2) the superimposition of the 3D models of the object and the trace, this latter being common practice in most of the case report publications. Starting from the characteristics of a mark, observed during the analysis phase, a confrontation was successively made with the features of each tool. On this basis, the main operator processed to the exclusion of the tools whose features were assessed as significantly different from the characteristics of the mark. Then, a qualitative concordance between the mark and the non-excluded tools was considered by superimposition of the 3D models: the models of the tool were put in touch with the model of the mock wound and if the positioning of both models did not show any correspondence of the general characteristics (shape and dimensions), the tool was excluded as possibly being at the origin of the trace.

Quantitative comparison: measurements

During the qualitative comparison, wounds and injury-causing tools were compared with each other, creating 'possible couples' that could match together by the morphological comparison (superimposition of the both). For all these couples (wound/ injury-causing tool) that were not excluded by the qualitative comparison, measurements were taken by the main operator. This was performed in order to assess if measurements could endorse the qualitative approach usually adopted in most of the case report publications. Straight lines and curve length, as well as angles encompassed in the mark, were constructed and measured through the GOM ATOS software. Measurements were chosen to allow a precise determination given the clarity of 3D models and the possibility of the software. Every measurement was taken three times in order to calculate a mean and estimate the uncertainty of the measurements through variance calculation. Then the corresponding measurements were taken (three times as well) on the tool that presumably could have caused the trace.

A comparison for each pair of measurements (wound/ injury-causing tool) was undertaken through an analysis of variance (ANOVA method, $p < 0.05$)[24]. This was used to evaluate the significance of difference between mean values considering the respective variance. For each pair of measurements, the result of the ANOVA indicated if the means had to be considered as statistically equal or not.

At the end of the comparison procedure, after considering and discussing the results of the qualitative and quantitative approaches, a list was produced stating for each mock wound the tools that could not be excluded as being at the origin of the trace. The operator did not to carry out an *evaluation* of the value of the association, except for the fact of being able to exclude a tool. As the mock wounds were produced under known conditions, the confrontation of the results provided by the main operator with the injury protocol (i.e. the tool that actually produced the mark) led to an evaluation of the overall methodology and to the formulation of paths for methodological improvements.

Results

The phase of analysis allowed classifying the 23 mock wounds in 3 groups corresponding to the degree of information conveyed by the mark. These groups were named as Type I, II and III, with the Type I carrying the most information and Type III the least. This classification was undertaken on the basis of the general features observed in each lesion, as no specific characteristics were noticed. Table 1 presents the 3 groups, with their specifications and the number of mock wounds distributed in each one. Figure 4 illustrates the models of the 23 mock wounds dispersed in the 3 groups.

Group	***Quality / specificity***	***# of traces***
Type I	Clear general pattern with high degree of specificity	9 mock wounds
Type II	General pattern not clearly printed or with low specificity	10 mock wounds
Type III	No distinguishable general pattern or high destruction of the surface	4 mock wounds

Table 1 - Groups that were discriminated on the basis of the analytical phase of the mock wounds.

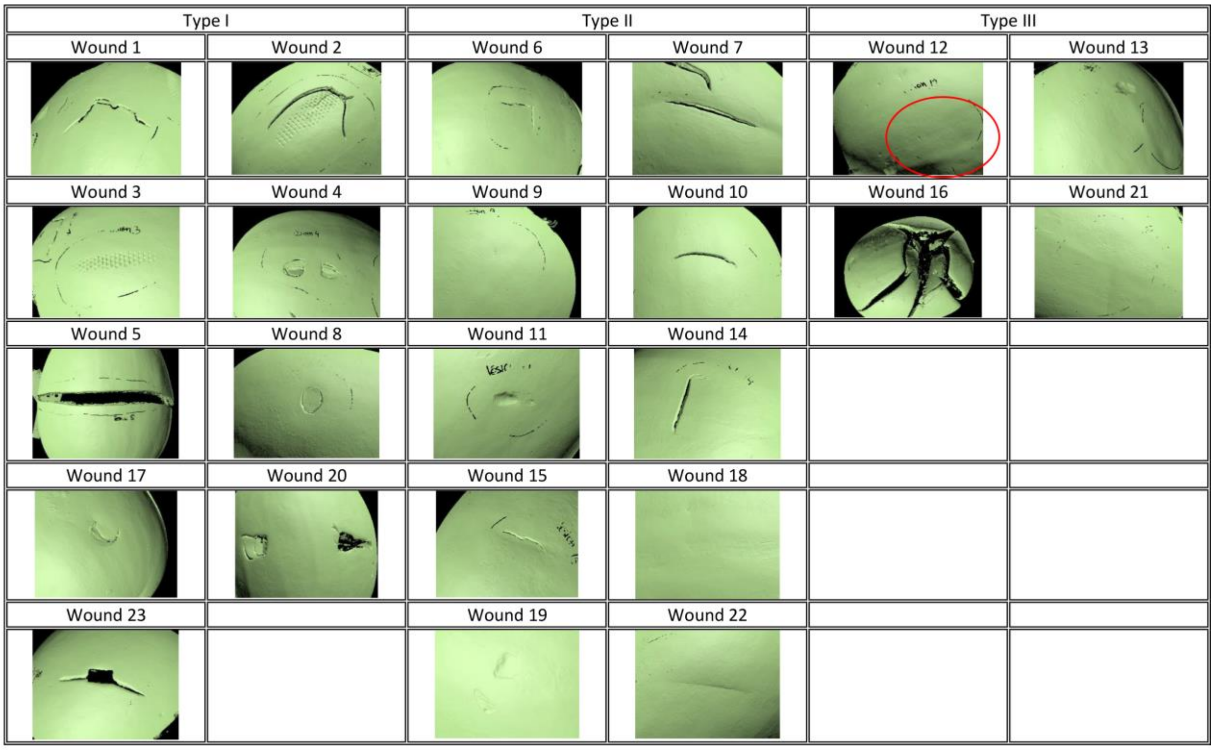

Figure 4 - 3D models of the 23 wounds dispersed in the 3 groups. (red circle : wound location)

The two dimensions process of qualitative comparison – considering both, the adequacy of the general features between a trace and a tool – and the following superimposition of their 3D models led to 3 situations. *a) exclusion of all but on.* For 12 mock wounds, all but one of the 15 tools were excluded. *b) exclusion of many, some remaining.* For 7 mock wounds, many tools were excluded but more than one (maximum 4) remained as possibly causing the trace. *c) no exclusion.* Finally, for 4 of the mock wounds, none of the tools could be excluded. Table 2 highlights the correlation between the results of the analytical phase and the outcome of the qualitative comparison: in general, we can see that the higher the quality/specificity of the trace, the higher the degree of exclusion.

	All but one tool excluded	***Several tools remaining possible (max. 4)***	***No exclusion (all tools remain possible)***
Type I	9	0	0
Type II	3	6	1
Type III	0	1	3
TOTAL	12	7	4

Table 2 - Correlation between the degree of information observed in the mock wounds (quality type) and the degree of exclusion achieved by qualitative comparison.

It is interesting to note that the first phase of the qualitative comparison, based on the direct adequacy of the general features observed in the mark and on the tools, appeared to be fairly discriminative as it allowed to proceed to the exclusion of a majority of the tools. For 6 of the 23 wounds, this first step of qualitative comparison resulted in the exclusion of all but one tool. Then for the 12 of the 17 remaining marks, the superimposition process led to further exclusions. 6 of these wounds got to the point that all but one tool were excluded, while for the 6 others, the superimposition lead to a significant reduction of the group of tools possibly causing the trace. (Figure 5)

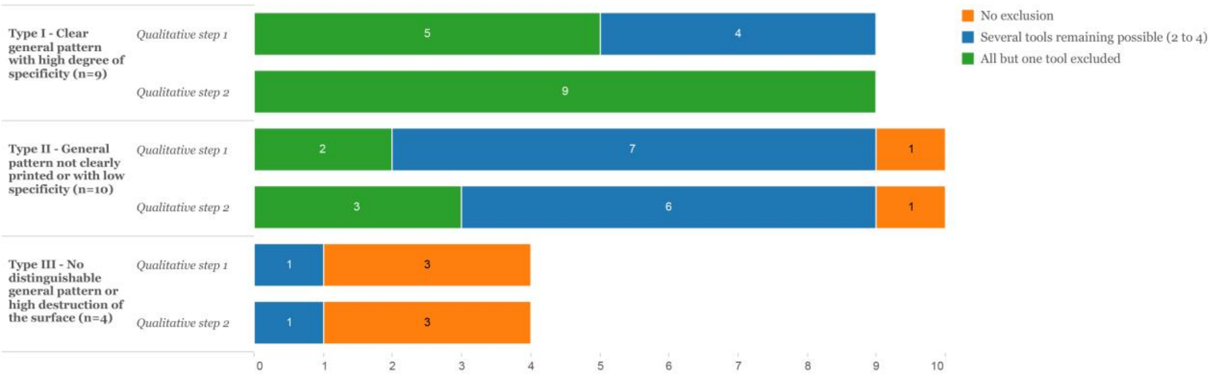

Figure 5 – Results from the analysis and the qualitative comparison

The 19 mock wounds for which exclusion could not be reached by the qualitative comparison were subjected to quantitative comparison: pairs of measurements made on marks and tools were confronted and statistically assessed. Depending on the general feature of the trace, several numbers of measurements were available for comparison as emphasised by the Figure 6. This figure shows that for two mock wounds, no measurement was possible.

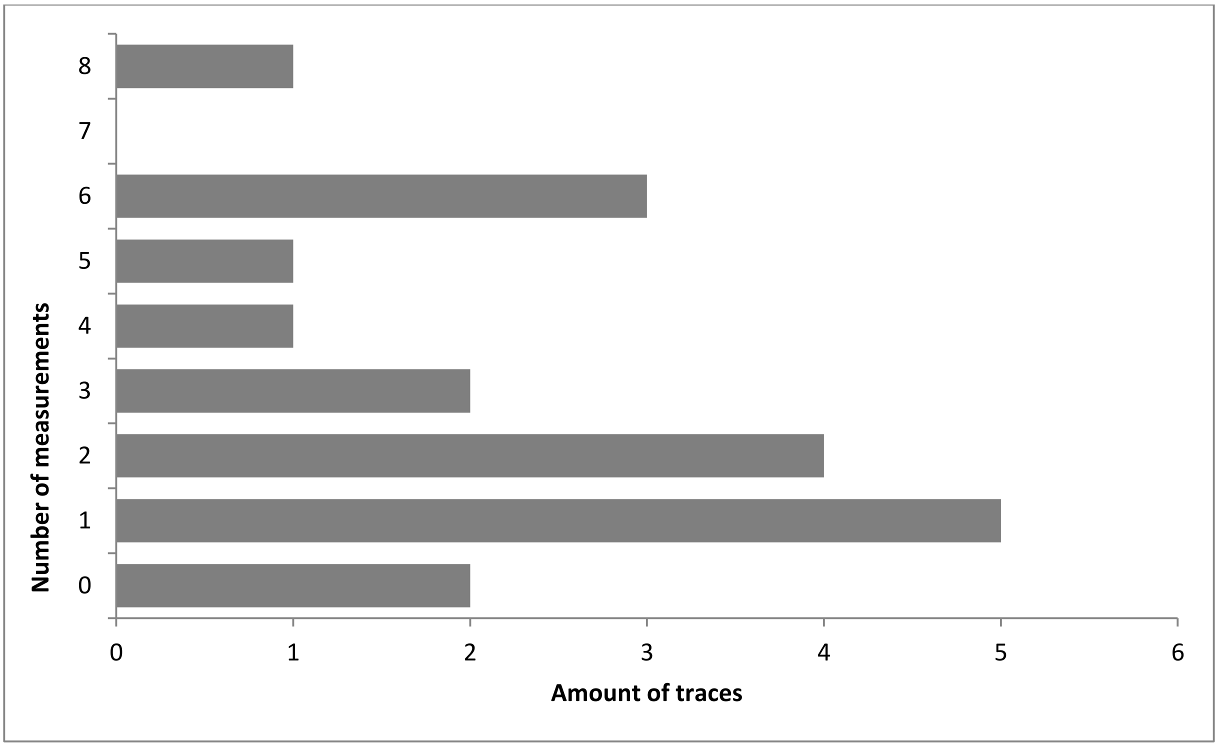

Figure 6 – Distribution of the number of measurements that were achievable on the 19 mock wounds considered for the quantitative step of comparison.

In total, 62 pairs of measurements (wound versus tool) were processed. For 58 of them, the ANOVA resulted to the rejection of the hypothesis of equality of means. In other words, in only 4 of the 62 comparisons, a measurement on a wound turned out to be equivalent to a corresponding measurement of a tool, keeping in mind that this tool was not excluded as possibly causing the wound on the basis of qualitative comparison. It is interesting to note that these equivalences arose on 4 different wounds, for which many measurements could be made, respectively 2, 4, 5 and 6 measurements. This means that the ANOVA revealed equivalence only for one of the pairs of measurements while denying it for all the other pairs of the same mock wound and the same object.

In general, we observed that the quantitative approach, based on the comparison of measurements taken on the mock wounds and the possible causing tools, was not able to corroborate the results of the qualitative comparisons. The statistical analysis made from the measurements suggested that all the tools could be excluded, yet keeping in mind that every measurement was only taken three times.

Confrontation of the results obtained by the qualitative comparison with the lesion protocol

As previously highlighted, 4 of the mock wounds could not lead to the exclusion of any of the tools, and no answer was proposed concerning the instruments that could have produced them. For 13 mock wounds, the two-steps qualitative comparison ended with a selection of possible causing instruments that contained the one that was actually used to produce the mark:

- for 10 of them, all but one tools could be excluded, and this has proven correct;
- for the 3 others, the instrument used to produce the trace was part of the selection of tools that were not excluded (respectively 2, 3 and 4 tools).

The comparison process led to incorrect answers for the 6 remaining mock wounds. In 4 cases, the injury-producing instrument was already wrongly excluded in the first phase of the qualitative comparison. For the other two, it was retained after the comparison of the general features, but (wrongly) excluded by superimposition of the 3D models. It is interesting to note that for two wounds, the comparison led to the situation that all but one tools were excluded, although the remaining instrument was actually not the one that produced the trace (Figure 7).

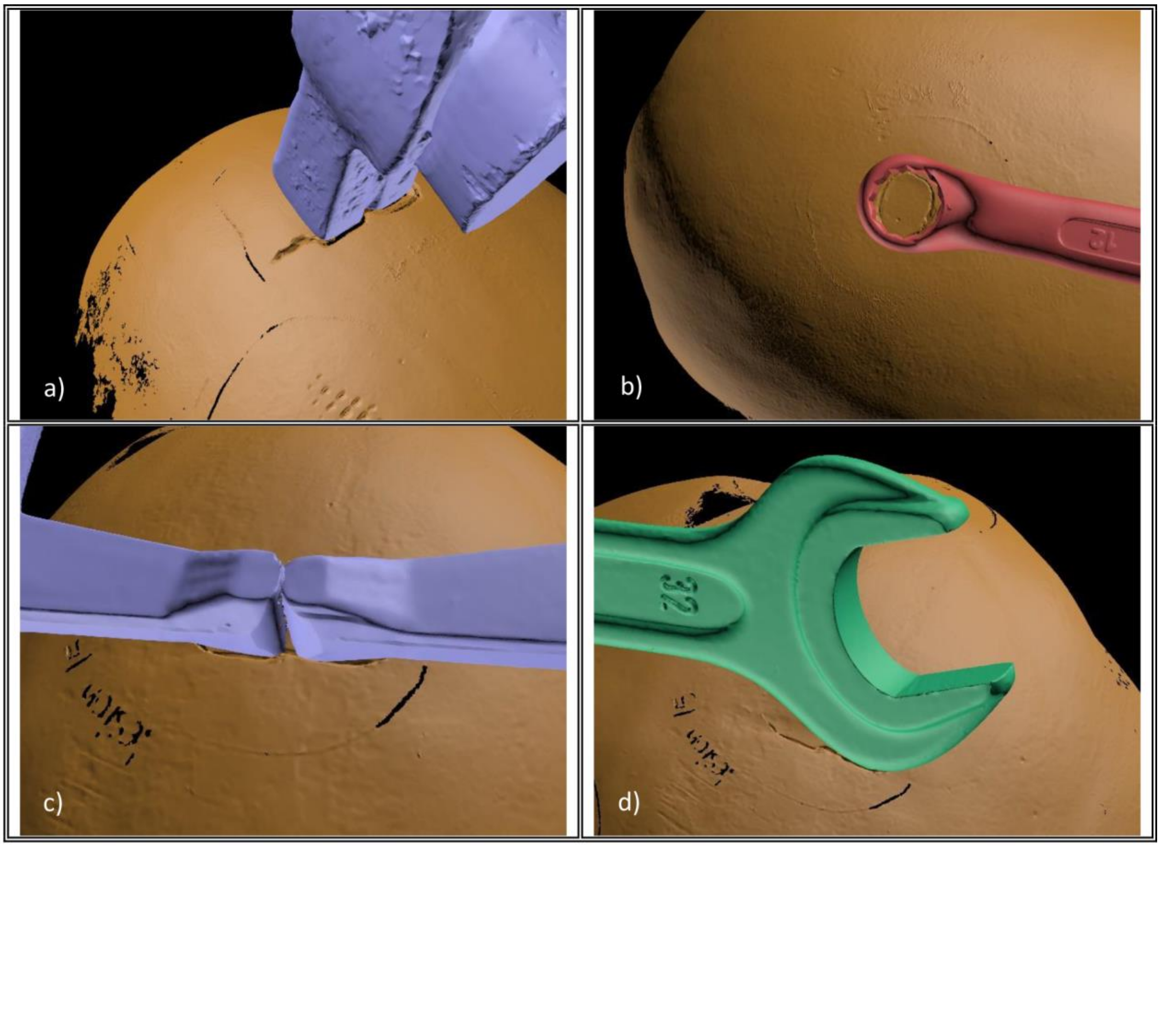

Figure 7 - a) Comparison between carpenter hammer and wound 1 giving a positive correlation; b) Comparison between silver wrench and wound 8 giving a negative correlation; c) Comparison between vise-grips and wound 15 giving a wrong positive correlation; d) Comparison between black wrench and wound 15 giving a correct positive correlation obtained after confrontation.

Considering these results in the light of the degree of information of the mark, assessed during the analysis phase, was very informative. Type I group was only composed of wounds for which only the right object was not excluded. Type III group was composed of 3 wounds for which no object could be excluded and one wound for which the object was wrongly excluded by superimposition. Type II group was composed by a mix of wrong and correct correlations (Table 3).

	Correct correlation	***Partially correct correlation***	***Wrong correlation***	***No correlation***	***Total***
Type I	9	0	0	0	9
Type II	1	3	5	1	10
Type III	0	0	1	3	4
Total	10	3	6	4	23

Table 3 - Relationship between groups of wounds and correct and wrong correlations. “Correct correlation” means that only the right object was not excluded; “Partially correct correlation” means that right object was in the list of not excluded objects; “Wrong correlation” means that the right object was falsely excluded; “No correlation” means that no comparison could be made.

Discussion

Compared to existing publications, our study was set up to include an *analysis* step with description of the wounds prior to the comparison process, in rudimentary application of ACE-V criteria. We had in mind to evaluate if criteria and methodology already existing in some forensic areas, such as fingermarks or shoemarks comparison, may serve as a basis for comparing 3D models of wounds and injury-causing instruments. This study was then appropriate to highlight limits in the current practice of 3D comparison, and to propose some necessary changes to prevent the perpetuation of this practice, and to avoid wrong correlations.

Our study provided a first assessment of the sensibility and specificity of the comparison process between a wound and a tool through the use of 3D models obtained by surface scanning. In an overarching perspective, the results show a significant number of wrong correlations that let us foresee that the process is not reliable enough for a systematic application in routine. But considering the different steps in detail, more optimistic conclusions can be drawn. These results have highlighted the crucial importance of an *analysis* step in 1) describing and assessing the information that can be obtained on a lesion in the perspective of a comparison process, and 2) setting the limits of the possible outcomes of a comparison process. This *analysis* phase appears as an imperative step before any comparison in order to prevent misinterpretations, false positives or over-determination in conclusion.

Concerning the choice of material, as the use of pork or anatomical bodies was discarded, both for practical and ethical reasons, we decided to use watermelon as reference material for the production of mock wounds. Thus, some others authors already used other types of fruit to simulated some body parts [25].This choice was also dictated by economic reasons: watermelons are inexpensive and easy to obtain. Even though the surface of watermelons has physical properties that are not truly comparable to human skin, we considered it as suitable for the sake of this study as the traces produced on their surface would have a better persistence and a good stability. Indeed, 'wounds' were well conserved in the material, even if, for some of them, tears appeared following the wound pattern. However we are fully aware that the use of this model is likely to produce more favourable results that can be expected on real skin. As already stated, it follows that our results cannot be generalised, and that they should inspire further research.

Regarding quantitative comparison, results showed that direct comparison of measurements between marks and tools was not a reliable approach. This finding is, however, not really surprising. Wounds produced by hitting a surface do not simply represent impressions of the tool; the dynamic interaction of the tool and the surface creates deformations that affect the morphological composition of the wound. By analogy, this situation is comparable to the one occurring during the formation of a shoemark through a walking process. The dynamic process results in the production of a trace whose dimensions are slightly larger than the ones of the sole of the shoe [26].

The different steps of this study were inspired by the ACE-V (Analysis, Comparison, Evaluation, and Verification) methodology that was first proposed for the friction ridge analysis (fingermarks, palm marks, footmarks) [20,21] and has been extended to other morphological traces in forensic science (tire tracks, tool prints, biological stains, documents, firearms, etc.). Even though our study relies on a rudimentary application of the ACE-V methodology, it nevertheless highlights foreseeable benefits of a thorough application of the methodology as a framework for morphological comparisons based on 3D models. On the basis of the information conveyed in the published articles related to comparisons of 3D models, that rely on reporting successful single cases, we understand that there is no agreed and reliable methodology that allows to evaluate the results of the comparison process and assess its meaning value (often presented as very convincing and probative in the aforementioned papers). In our study, we showed that the comparison process could lead to unsuccessful results, and even to false positive conclusion, emphasising the need to anchor the comparison process in a robust methodological framework. In our opinion, it is important to study in detail the benefits and limitations of 3D morphological comparison process based on surface scanning models. Some welcome initiatives have been made in this perspective [26,15,18], but unfortunately too few to use the existing literature for supporting these scientific methods.

As previously mentioned, our study suggests that the ACE-V methodology could be very valuable, but it also clearly shows current limitations that must be further studied. The phase of *analysis* must be improved and better formalised. Formation and deformation processes of the wound must also be studied and taken into account during this *analysis* step. Qualitative comparison depends in a great part of the experience and subjectivity of the expert. It is difficult to give a scientific weight to this type of comparison. That is why a quantitative comparison must be done in addition. Here, the quantitative approach for comparison failed, and therefore has to be reconsidered for this methodology. In order to make a stronger quantitative comparison as well as a stronger qualitative comparison, it is imperative to compare the trace with a reference mark (mark created in controlled conditions with the suspected tool) rather than with the suspected tool itself. Inspiration should be found in the fingermarks [27,21,28] and footmarks areas [29-31].

The limitations of the device also have some influence on the study. As it was said at the beginning of the article, when objects are too dark or too shiny they had to be sprayed with a specific solution. Still the results are not perfect and it is difficult for the 3D scanner to represent the whole surface of the objects. Some tiny areas were not captured and then do not appear on the 3D model. As it is a surface scanner, there are also some limitations in representing deeper structures of the objects. Therefore, in our study, profound parts of the wounds were not represented in the 3D model. These elements reduce the quality of the analysis and the comparison. Our study also suffers from some specific limitations, like the model that is not human. Another model closer to human skin has to be tested if human skin cannot still be used for ethical reasons. Furthermore, the whole study was made only with one observer, because it was a first research to define criteria. It will be essential to test the final developed method with different observers (inter-personal variation).

These limitations known, it will be important to set up a protocol for the use of 3D-surface scanners for blunt wounds in a further study. Criteria need to be defined, precise methodology needs to be developed, and finally more adapted material will be used to produce the mock wounds.

Conclusion

Results obtained in our study shed light on the problem of the qualitative and quantitative approaches applied to morphological comparisons based on 3D surface models in forensic science, and legal medicine in particular. They strongly suggest that further research is needed to better understand the limits of such models, and to set up a transparent methodology that could support informative and reliable conclusions. This would encompass in particular (but not exhaustively) the aspects of mark formation, interaction between the skin and an object, the study of the wound and the information that could be extracted from it. And, of course, a methodology inspired by methods already applied in forensic science could favourably be developed. Watermelons were a good model to begin with but models even more similar to the skin have to be found. Further studies are planned following this one, especially working on comparing traces with reference marks.

Conflicts of interest: The authors have no conflicts of interest to disclose.

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An exploratory study toward the contribution of 3D surface scanning for association of an injury with its causing instrument

Stella Fahrni[1,2], Olivier Delémont[1], Lorenzo Campana[2], Silke Grabherr[2]

[1] School of Criminal Justice, University of Lausanne, 1015 Lausanne-Dorigny, Switzerland.

[2] University Centre for Legal Medicine Lausanne-Geneva, Chemin de la Vulliette 4, 1000 Lausanne 25, Switzerland.

Corresponding author:

Stella Fahrni

School of Criminal Justice, University of Lausanne, 1015 Lausanne-Dorigny, Switzerland

Stella.Fahrni@unil.ch

+41 (0) 21 692 46 18

ORCID: 0000-0003-1643-6100

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Abstract

3D surface scanning is a technique brought forward for wound documentation and analysis in order to identify injury-causing tools in legal medicine and forensic science. Although many case reports have been published, little is known about the methodology employed by the authors.

The study reported here is exploratory in nature, and its main purpose was to get a first evaluation of the ability of an operator, by means of 3D surface scanning and following a simple methodology, to correctly exclude or associate an incriminated tool as the source of a mock wound. Based on these results, an assessment on the possibility to define a structured methodology that could be suitable for this use was proposed.

Blunt tools were used to produce “wounds” on watermelons. Both wounds and tools were scanned with a non-contact optical surface 3D digitising system. Analysis of the obtained 3D models of wounds and tools was undertaken separately. This analytical phase was followed by a qualitative and a quantitative comparison.

Results showed that in more than half of the cases, we obtained correct association but the prevalence of wrong association was still high due to mark deformation and other limitations.

Even if the findings of this exploratory study cannot be generalised, they suggest that the simple and direct comparison process is not reliable enough for systematic routine application. The article highlights the importance of an analysis phase preceding the comparison step. Limitations of the technique, ensuing needs and possible paths for improvement are also expounded.

Keywords

forensic imaging; 3D modelling; methodology; ACE-V; analysis.

Introduction

During the last decade of the 20th century, the improvement of digital photography [1,2] and imaging techniques enabled the proliferation of solutions to record 3D data through the use of digital photogrammetry and lasergrammetry [3-7]. In legal medicine, especially in forensic traumatology, another alternative of optical scanning device, mainly known as 3D surface scanning, was then put forward for the three-dimensional analysis of the volumetric adequacy of a wound and a possible injury-causing instrument [8]. The contribution of 3D surface scanning instrumentation was mainly emphasised through specific applications, mostly in combination with other non-invasive imaging techniques such as MDCT (multi-detector computed tomography) [9-13] or MRI (magnetic resonance imaging) [10,12,13]. These specific applications were shown by case examples, mostly cases of traffic accident reconstructions [4,5], comparisons of wounds with the injury-causing instrument [3,14,15,6,16,7], and event scenario assessments [4,5]. Several related case reports praised the high quality of the images and other general advantages of the 3D surface scanning techniques, such as an objective and non-invasive 3D documentation, the high resolution and the accuracy [4,17,8].

In the existing literature, no detailed information is provided about parameters and conditions of application of the 3D scanning techniques. Using 3D data remains a mostly veiled and implicit process: the methodological framework for the performed analysis, especially considering the volumetric comparison of the sets of 3D data, is rarely explained, if not undefined. It generally relies on the superimposition of 3D models generated from the surface scanning data of the mark (the wound) and of the suspected injury-causing instrument. The discussion of the results of this superimposition and their meaning are in most cases not emphasised. Generally, the methodological approach for the implementation of the technique, its deployment in the multidisciplinary and collaborative process of (criminal) event reconstruction, and the scientific justification of the conclusions drawn from the application of the 3D imaging techniques are not explicitly considered. Examining the pertaining literature, we observe an over-representation of case reports, yet convincing, and only a very small number of systematic and rigorous basic research studies [18,19].

The present study was focussed on the use of 3D surface scanning technique for the general process of comparison between a mark – representing a wound – and an object. In some other fields in forensic science, a methodological approach, called ACE-V (Analysis, Comparison, Evaluation and Verification), is used for the study and comparison of traces [20,21]. The procedure followed in our study was inspired by this ACE-V process. We did not claim to setup a complete and systematic study, but to implement an experimental design that could unveil the pitfalls of a subjective comparison made from 3D data. The purpose was to explore the ability of an operator, by means of 3D surface scanning, to take a decision on the association/exclusion of an incriminated tool as the source of a mock wound. Ideally, the operator was told to try to attribute the mark to one specific object. On the basis of the results of this exploratory set of experiments, we tried to delineate a possible methodology that could overcome the highlighted limitations. To our point of view, such a methodology should encompass several sequential steps that should be clearly defined and formalised, following the ACE-V approach: the description of wound, the analysis of its informational content, the comparison with a reference trace made by an instrument, and the assessment of the value of this comparison.

Material and Methods

This study was divided in sequential steps: an initial phase of analysis was undertaken separately for each trace and each object. It was followed by a qualitative comparison taking into account the general features observed during the analytical phase and the superimposition of the 3D models of the traces and the objects. Finally, a quantitative step was carried out by comparing pairs of measurements between a mark and an object.

Specimens' preparation

We composed a set of blunt instruments by collecting 15 household tools, rigid objects easily accessible in daily life or able to cause blunt injuries: pliers, black wrench, silver wrench, monkey wrench, shower head, chair leg, hammer, axe, poker, jack handle, carpenter hammer, vise-grips, sledge hammer, file, bat.

Twenty-three marks, referred as 'mock wounds', were produced by seven different persons striking the surface of watermelons (average length between 20 and 25 cm and average diameter of approximately 20 cm) with the fifteen instruments, at least one and maximum twice per tool. This way of wound production was chosen because it results in a realistic blunt force trauma pattern, and that it was not aimed to compare wounds with each other. On each watermelon, three or four wounds were made, using two or three tools. Each watermelon, each wound as well as each tool was individually labelled. After the production of a mock wound, the person that produced it, filled in a so-called 'lesion protocol' with all the details related to the tool used and conditions of mark production. The seven volunteers who hit the watermelons were 3 women and 4 men aged between 29 and 64 years old. No specific rules were given to them, just to strike the watermelons as they would hurt somebody. This phase took place indoor, in the autopsy room. The main researcher in charge of the study did not take part to this production phase of mock wounds, nor was she informed about which tool was used to produce each of the marks.

3D data acquisition: from scanning to modelling

3D surface measurement was processed through a non-contact optical 3D digitising system Gom ATOS Compact Scan 5M (Gom, Braunschweig, Germany)(Figure 1), which allows to obtain 3D models from real data with high resolution and accuracy. The functioning of this scanner relies on the fringe pattern projection (blue light) of adapting array of stripes that impact the surface to be measured. Two 5-million-pixels cameras record the deflections of the stripes induced on the shape of the surface. By triangulation principle, the measurements from both cameras are merged in a point cloud representing the surface, with high resolution and accuracy. [22,23]. Acquisition was controlled through the ATOS Professional V7.5 SR2 software package, also used for some further treatments in conjunction with a 3ds Max 2013 software. Two different measuring volumes (MV) – corresponding to different pairs of camera lenses – were used on the scanner depending on the size of the object: MV 150 (resolution up to 0.062 mm) and MV 300 (resolution up to 0.124 mm). This required in accordance the use of two different calibration panels: CP40/MV170 and CP40/MV320.

Figure 1 – Gom ATOS Compact Scan 5M

A calibration of the scanner was regularly carried out during the period of scanning, and in particular every time the measuring volume was changed in order to assure minimal deviation in measurements. Markers were placed around the mock wounds, on the surfaces of the tools as well as on the support of the tools. Mock wounds and tools were scanned in a room at ambient temperature (around 21°C) under controlled and stable luminosity. Parasite movements were reduced to a minimum level by fixing the different parts of the camera to a tripod and by working in an isolated room. Objects whose surfaces were too shiny or dark were first sprayed with a solution of titanium dioxide (TiO_2) powder in ethanol, to reduce gloss and prevent the production of artefacts.

Tool scanning was performed in a two-step process: the front side was first digitised, then the object was turned over on the support and the back was scanned. Marks on watermelons did not need such a process as they were situated only on one side of the fruits. Each watermelon was scanned with the MV300 measuring volume (300 x 230 x 230 mm), as the majority of the tools (Figure 2). For some smaller objects, the MV150 measuring volume (150 x 110 x 110 mm) was preferred. A complete operation of 3D data acquisition for a mock wound required an average of 15 to 30 minutes, and 30 minutes to more than one hour per tool depending on the complexity of the surface. Watermelons were scanned within one to four days after the production of the mock wounds, following availability of the instrumentation and of the autopsy room. Watermelons were kept in a fridge between the production of the wound and the scanning process.

The points corresponding to the support of the objects were erased from the 3D scans using the Gom ATOS software. Both faces of the tools were merged together and 3D models were created from the point clouds by polygon meshing with as many details as possible (Figure 3). No further treatment was processed on these 3D models (for instance, no automatic filling of some holes on the surface of the model).

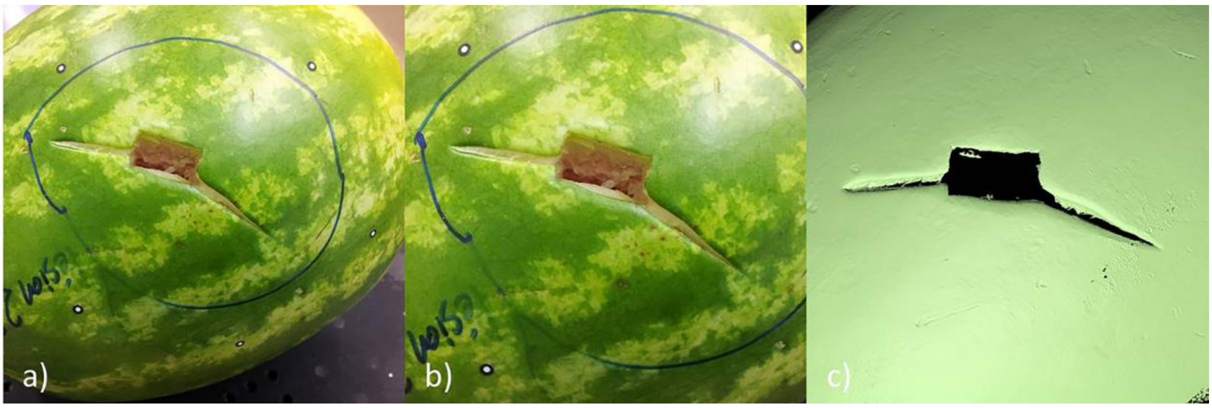

Figure 2 - Example of a scanned lesion. a)-b) Photographs of lesion 23 on the watermelon; c) 3D model of lesion 23 obtained from the GOM scanner

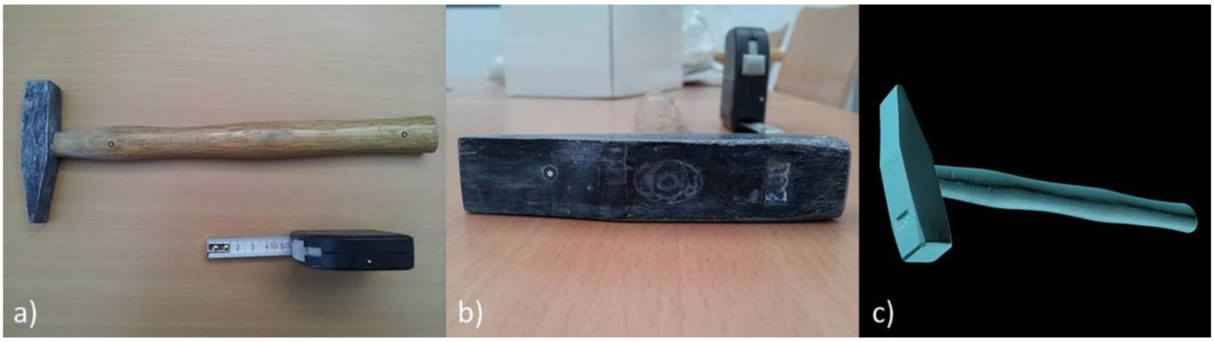

Figure 3 - Example of a scanned object. a)-b) Photographs of the hammer; c) 3D model of the hammer obtained from the GOM scanner

Qualitative analysis and comparison

The 3D models of each mock wound and each tool were separately scrutinised by means of the 3DS Max® software (edition 2014, Autodesk). During this phase of *analysis*, each mark was examined by the main operator; the type and location of the visible characteristics were assessed enabling to evaluate the confidence on the outcome of a comparison process. In this perspective, the quality and quantity of information present and useful for a comparison process were systematically considered and annotated. For every mark, general features, such as shape and dimensions, and more specific characteristics (patterns, particularities, etc.) were compiled. When possible, the direction of production of the mark was also considered. From these elements, the marks were distributed into three categories according to the type and quality of information extracted:

- Type I: Clear general pattern with high degree of specificity;
- Type II: General pattern not clearly printed or with low specificity;
- Type III: No distinguishable general pattern or high destruction of the surface.

This analysis step was also undertaken by the main operator on every tool, gathering information about the general features and measurable characteristics on each one of them.

Then, a *qualitative comparison* took place for each trace, taking sequentially into account each of the considered tools. This qualitative approach included two dimensions: 1) the direct comparison of the general features and particularities observed during the analysis phase, and 2) the superimposition of the 3D models of the object and the trace, this latter being common practice in most of the case report publications. Starting from the characteristics of a mark, observed during the analysis phase, a confrontation was successively made with the features of each tool. On this basis, the main operator processed to the exclusion of the tools whose features were assessed as significantly different from the characteristics of the mark. Then, a qualitative concordance between the mark and the non-excluded tools was considered by superimposition of the 3D models: the models of the tool were put in touch with the model of the mock wound and if the positioning of both models did not show any correspondence of the general characteristics (shape and dimensions), the tool was excluded as possibly being at the origin of the trace.

Quantitative comparison: measurements

During the qualitative comparison, wounds and injury-causing tools were compared with each other, creating 'possible couples' that could match together by the morphological comparison (superimposition of the both). For all these couples (wound/ injury-causing tool) that were not excluded by the qualitative comparison, measurements were taken by the main operator. This was performed in order to assess if measurements could endorse the qualitative approach usually adopted in most of the case report publications. Straight lines and curve length, as well as angles encompassed in the mark, were constructed and measured through the GOM ATOS software. Measurements were chosen to allow a precise determination given the clarity of 3D models and the possibility of the software. Every measurement was taken three times in order to calculate a mean and estimate the uncertainty of the measurements through variance calculation. Then the corresponding measurements were taken (three times as well) on the tool that presumably could have caused the trace.

A comparison for each pair of measurements (wound/ injury-causing tool) was undertaken through an analysis of variance (ANOVA method, $p < 0.05$)[24]. This was used to evaluate the significance of difference between mean values considering the respective variance. For each pair of measurements, the result of the ANOVA indicated if the means had to be considered as statistically equal or not.

At the end of the comparison procedure, after considering and discussing the results of the qualitative and quantitative approaches, a list was produced stating for each mock wound the tools that could not be excluded as being at the origin of the trace. The operator did not to carry out an *evaluation* of the value of the association, except for the fact of being able to exclude a tool. As the mock wounds were produced under known conditions, the confrontation of the results provided by the main operator with the injury protocol (i.e. the tool that actually produced the mark) led to an evaluation of the overall methodology and to the formulation of paths for methodological improvements.

Results

The phase of analysis allowed classifying the 23 mock wounds in 3 groups corresponding to the degree of information conveyed by the mark. These groups were named as Type I, II and III, with the Type I carrying the most information and Type III the least. This classification was undertaken on the basis of the general features observed in each lesion, as no specific characteristics were noticed. Table 1 presents the 3 groups, with their specifications and the number of mock wounds distributed in each one. Figure 4 illustrates the models of the 23 mock wounds dispersed in the 3 groups.

Group	***Quality / specificity***	***# of traces***
Type I	Clear general pattern with high degree of specificity	9 mock wounds
Type II	General pattern not clearly printed or with low specificity	10 mock wounds
Type III	No distinguishable general pattern or high destruction of the surface	4 mock wounds

Table 1 - Groups that were discriminated on the basis of the analytical phase of the mock wounds.

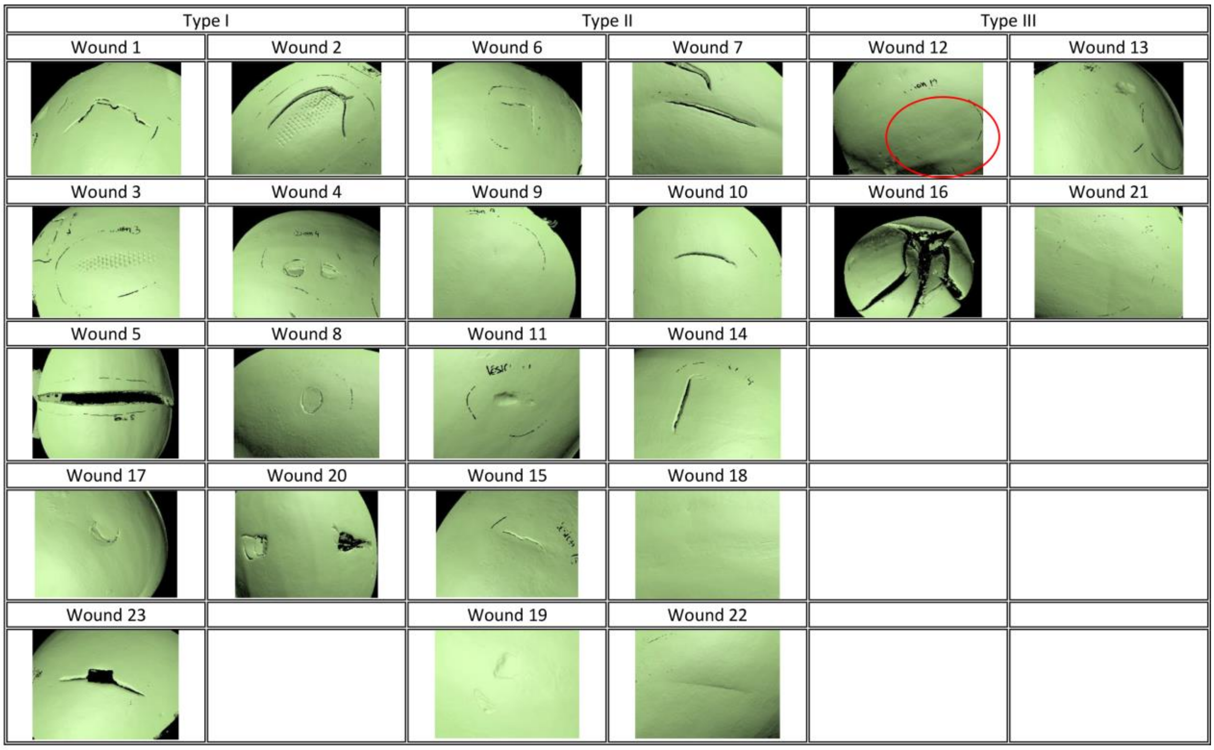

Figure 4 - 3D models of the 23 wounds dispersed in the 3 groups. (red circle : wound location)

The two dimensions process of qualitative comparison – considering both, the adequacy of the general features between a trace and a tool – and the following superimposition of their 3D models led to 3 situations. *a) exclusion of all but on.* For 12 mock wounds, all but one of the 15 tools were excluded. *b) exclusion of many, some remaining.* For 7 mock wounds, many tools were excluded but more than one (maximum 4) remained as possibly causing the trace. *c) no exclusion.* Finally, for 4 of the mock wounds, none of the tools could be excluded. Table 2 highlights the correlation between the results of the analytical phase and the outcome of the qualitative comparison: in general, we can see that the higher the quality/specificity of the trace, the higher the degree of exclusion.

	All but one tool excluded	***Several tools remaining possible (max. 4)***	***No exclusion (all tools remain possible)***
Type I	9	0	0
Type II	3	6	1
Type III	0	1	3
TOTAL	12	7	4

Table 2 - Correlation between the degree of information observed in the mock wounds (quality type) and the degree of exclusion achieved by qualitative comparison.

It is interesting to note that the first phase of the qualitative comparison, based on the direct adequacy of the general features observed in the mark and on the tools, appeared to be fairly discriminative as it allowed to proceed to the exclusion of a majority of the tools. For 6 of the 23 wounds, this first step of qualitative comparison resulted in the exclusion of all but one tool. Then for the 12 of the 17 remaining marks, the superimposition process led to further exclusions. 6 of these wounds got to the point that all but one tool were excluded, while for the 6 others, the superimposition lead to a significant reduction of the group of tools possibly causing the trace. (Figure 5)

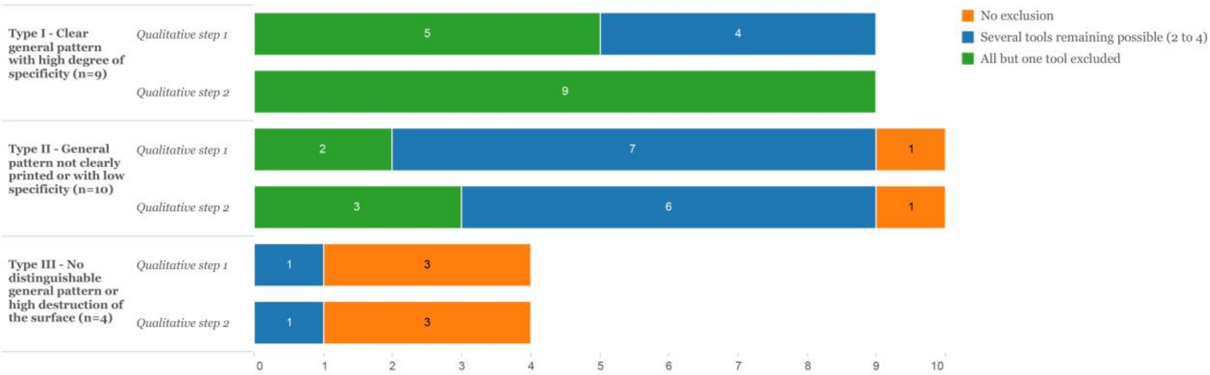

Figure 5 – Results from the analysis and the qualitative comparison

The 19 mock wounds for which exclusion could not be reached by the qualitative comparison were subjected to quantitative comparison: pairs of measurements made on marks and tools were confronted and statistically assessed. Depending on the general feature of the trace, several numbers of measurements were available for comparison as emphasised by the Figure 6. This figure shows that for two mock wounds, no measurement was possible.

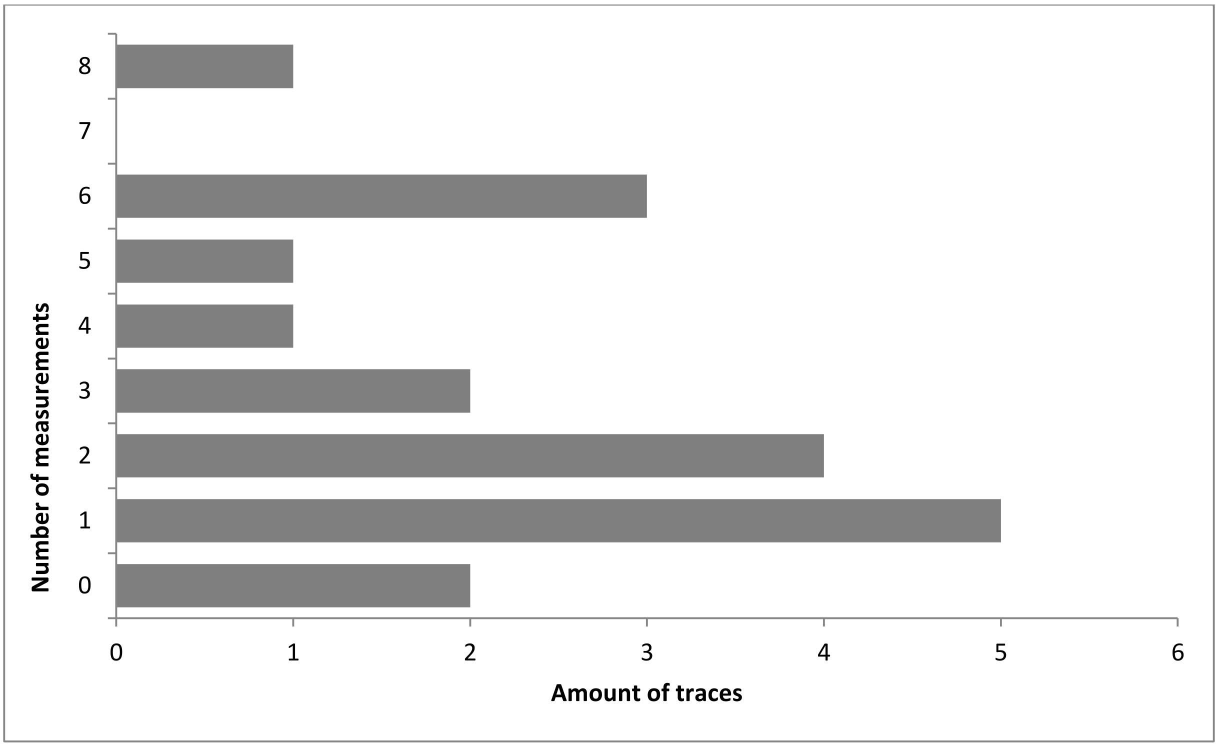

Figure 6 – Distribution of the number of measurements that were achievable on the 19 mock wounds considered for the quantitative step of comparison.

In total, 62 pairs of measurements (wound versus tool) were processed. For 58 of them, the ANOVA resulted to the rejection of the hypothesis of equality of means. In other words, in only 4 of the 62 comparisons, a measurement on a wound turned out to be equivalent to a corresponding measurement of a tool, keeping in mind that this tool was not excluded as possibly causing the wound on the basis of qualitative comparison. It is interesting to note that these equivalences arose on 4 different wounds, for which many measurements could be made, respectively 2, 4, 5 and 6 measurements. This means that the ANOVA revealed equivalence only for one of the pairs of measurements while denying it for all the other pairs of the same mock wound and the same object.

In general, we observed that the quantitative approach, based on the comparison of measurements taken on the mock wounds and the possible causing tools, was not able to corroborate the results of the qualitative comparisons. The statistical analysis made from the measurements suggested that all the tools could be excluded, yet keeping in mind that every measurement was only taken three times.

Confrontation of the results obtained by the qualitative comparison with the lesion protocol

As previously highlighted, 4 of the mock wounds could not lead to the exclusion of any of the tools, and no answer was proposed concerning the instruments that could have produced them. For 13 mock wounds, the two-steps qualitative comparison ended with a selection of possible causing instruments that contained the one that was actually used to produce the mark:

- for 10 of them, all but one tools could be excluded, and this has proven correct;
- for the 3 others, the instrument used to produce the trace was part of the selection of tools that were not excluded (respectively 2, 3 and 4 tools).

The comparison process led to incorrect answers for the 6 remaining mock wounds. In 4 cases, the injury-producing instrument was already wrongly excluded in the first phase of the qualitative comparison. For the other two, it was retained after the comparison of the general features, but (wrongly) excluded by superimposition of the 3D models. It is interesting to note that for two wounds, the comparison led to the situation that all but one tools were excluded, although the remaining instrument was actually not the one that produced the trace (Figure 7).

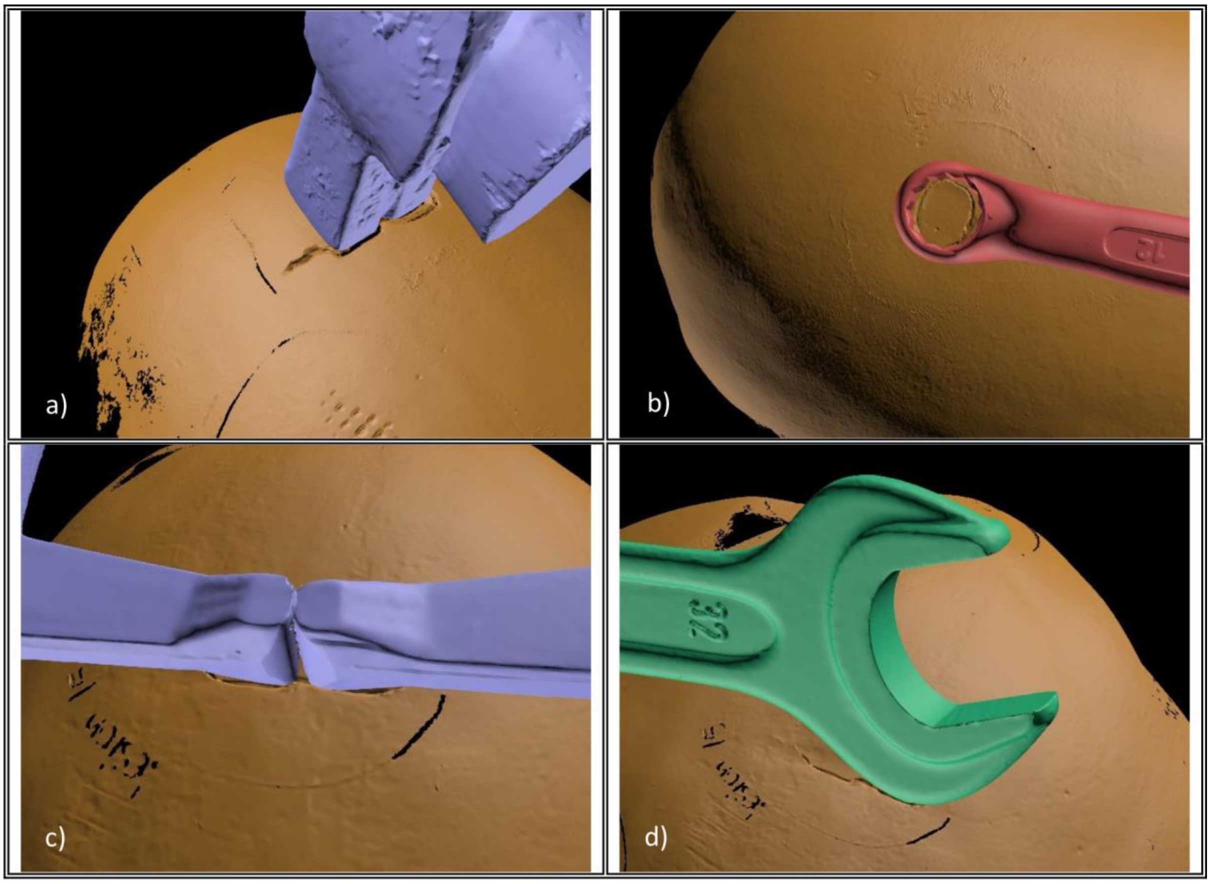

Figure 7 - a) Comparison between carpenter hammer and wound 1 giving a positive correlation; b) Comparison between silver wrench and wound 8 giving a negative correlation; c) Comparison between vise-grips and wound 15 giving a wrong positive correlation; d) Comparison between black wrench and wound 15 giving a correct positive correlation obtained after confrontation.

Considering these results in the light of the degree of information of the mark, assessed during the analysis phase, was very informative. Type I group was only composed of wounds for which only the right object was not excluded. Type III group was composed of 3 wounds for which no object could be excluded and one wound for which the object was wrongly excluded by superimposition. Type II group was composed by a mix of wrong and correct correlations (Table 3).

	Correct correlation	***Partially correct correlation***	***Wrong correlation***	***No correlation***	***Total***
Type I	9	0	0	0	9
Type II	1	3	5	1	10
Type III	0	0	1	3	4
Total	10	3	6	4	23

Table 3 - Relationship between groups of wounds and correct and wrong correlations. "Correct correlation" means that only the right object was not excluded; "Partially correct correlation" means that right object was in the list of not excluded objects; "Wrong correlation" means that the right object was falsely excluded; "No correlation" means that no comparison could be made.

Discussion

Compared to existing publications, our study was set up to include an *analysis* step with description of the wounds prior to the comparison process, in rudimentary application of ACE-V criteria. We had in mind to evaluate if criteria and methodology already existing in some forensic areas, such as fingermarks or shoemarks comparison, may serve as a basis for comparing 3D models of wounds and injury-causing instruments. This study was then appropriate to highlight limits in the current practice of 3D comparison, and to propose some necessary changes to prevent the perpetuation of this practice, and to avoid wrong correlations.

Our study provided a first assessment of the sensibility and specificity of the comparison process between a wound and a tool through the use of 3D models obtained by surface scanning. In an overarching perspective, the results show a significant number of wrong correlations that let us foresee that the process is not reliable enough for a systematic application in routine. But considering the different steps in detail, more optimistic conclusions can be drawn. These results have highlighted the crucial importance of an *analysis* step in 1) describing and assessing the information that can be obtained on a lesion in the perspective of a comparison process, and 2) setting the limits of the possible outcomes of a comparison process. This *analysis* phase appears as an imperative step before any comparison in order to prevent misinterpretations, false positives or over-determination in conclusion.

Concerning the choice of material, as the use of pork or anatomical bodies was discarded, both for practical and ethical reasons, we decided to use watermelon as reference material for the production of mock wounds. Thus, some others authors already used other types of fruit to simulated some body parts [25].This choice was also dictated by economic reasons: watermelons are inexpensive and easy to obtain. Even though the surface of watermelons has physical properties that are not truly comparable to human skin, we considered it as suitable for the sake of this study as the traces produced on their surface would have a better persistence and a good stability. Indeed, 'wounds' were well conserved in the material, even if, for some of them, tears appeared following the wound pattern. However we are fully aware that the use of this model is likely to produce more favourable results that can be expected on real skin. As already stated, it follows that our results cannot be generalised, and that they should inspire further research.

Regarding quantitative comparison, results showed that direct comparison of measurements between marks and tools was not a reliable approach. This finding is, however, not really surprising. Wounds produced by hitting a surface do not simply represent impressions of the tool; the dynamic interaction of the tool and the surface creates deformations that affect the morphological composition of the wound. By analogy, this situation is comparable to the one occurring during the formation of a shoemark through a walking process. The dynamic process results in the production of a trace whose dimensions are slightly larger than the ones of the sole of the shoe [26].

The different steps of this study were inspired by the ACE-V (Analysis, Comparison, Evaluation, and Verification) methodology that was first proposed for the friction ridge analysis (fingermarks, palm marks, footmarks) [20,21] and has been extended to other morphological traces in forensic science (tire tracks, tool prints, biological stains, documents, firearms, etc.). Even though our study relies on a rudimentary application of the ACE-V methodology, it nevertheless highlights foreseeable benefits of a thorough application of the methodology as a framework for morphological comparisons based on 3D models. On the basis of the information conveyed in the published articles related to comparisons of 3D models, that rely on reporting successful single cases, we understand that there is no agreed and reliable methodology that allows to evaluate the results of the comparison process and assess its meaning value (often presented as very convincing and probative in the aforementioned papers). In our study, we showed that the comparison process could lead to unsuccessful results, and even to false positive conclusion, emphasising the need to anchor the comparison process in a robust methodological framework. In our opinion, it is important to study in detail the benefits and limitations of 3D morphological comparison process based on surface scanning models. Some welcome initiatives have been made in this perspective [26,15,18], but unfortunately too few to use the existing literature for supporting these scientific methods.

As previously mentioned, our study suggests that the ACE-V methodology could be very valuable, but it also clearly shows current limitations that must be further studied. The phase of *analysis* must be improved and better formalised. Formation and deformation processes of the wound must also be studied and taken into account during this *analysis* step. Qualitative comparison depends in a great part of the experience and subjectivity of the expert. It is difficult to give a scientific weight to this type of comparison. That is why a quantitative comparison must be done in addition. Here, the quantitative approach for comparison failed, and therefore has to be reconsidered for this methodology. In order to make a stronger quantitative comparison as well as a stronger qualitative comparison, it is imperative to compare the trace with a reference mark (mark created in controlled conditions with the suspected tool) rather than with the suspected tool itself. Inspiration should be found in the fingermarks [27,21,28] and footmarks areas [29-31].

The limitations of the device also have some influence on the study. As it was said at the beginning of the article, when objects are too dark or too shiny they had to be sprayed with a specific solution. Still the results are not perfect and it is difficult for the 3D scanner to represent the whole surface of the objects. Some tiny areas were not captured and then do not appear on the 3D model. As it is a surface scanner, there are also some limitations in representing deeper structures of the objects. Therefore, in our study, profound parts of the wounds were not represented in the 3D model. These elements reduce the quality of the analysis and the comparison. Our study also suffers from some specific limitations, like the model that is not human. Another model closer to human skin has to be tested if human skin cannot still be used for ethical reasons. Furthermore, the whole study was made only with one observer, because it was a first research to define criteria. It will be essential to test the final developed method with different observers (inter-personal variation).

These limitations known, it will be important to set up a protocol for the use of 3D-surface scanners for blunt wounds in a further study. Criteria need to be defined, precise methodology needs to be developed, and finally more adapted material will be used to produce the mock wounds.

Conclusion

Results obtained in our study shed light on the problem of the qualitative and quantitative approaches applied to morphological comparisons based on 3D surface models in forensic science, and legal medicine in particular. They strongly suggest that further research is needed to better understand the limits of such models, and to set up a transparent methodology that could support informative and reliable conclusions. This would encompass in particular (but not exhaustively) the aspects of mark formation, interaction between the skin and an object, the study of the wound and the information that could be extracted from it. And, of course, a methodology inspired by methods already applied in forensic science could favourably be developed. Watermelons were a good model to begin with but models even more similar to the skin have to be found. Further studies are planned following this one, especially working on comparing traces with reference marks.

Conflicts of interest: The authors have no conflicts of interest to disclose.

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Figure 1

Figure 2

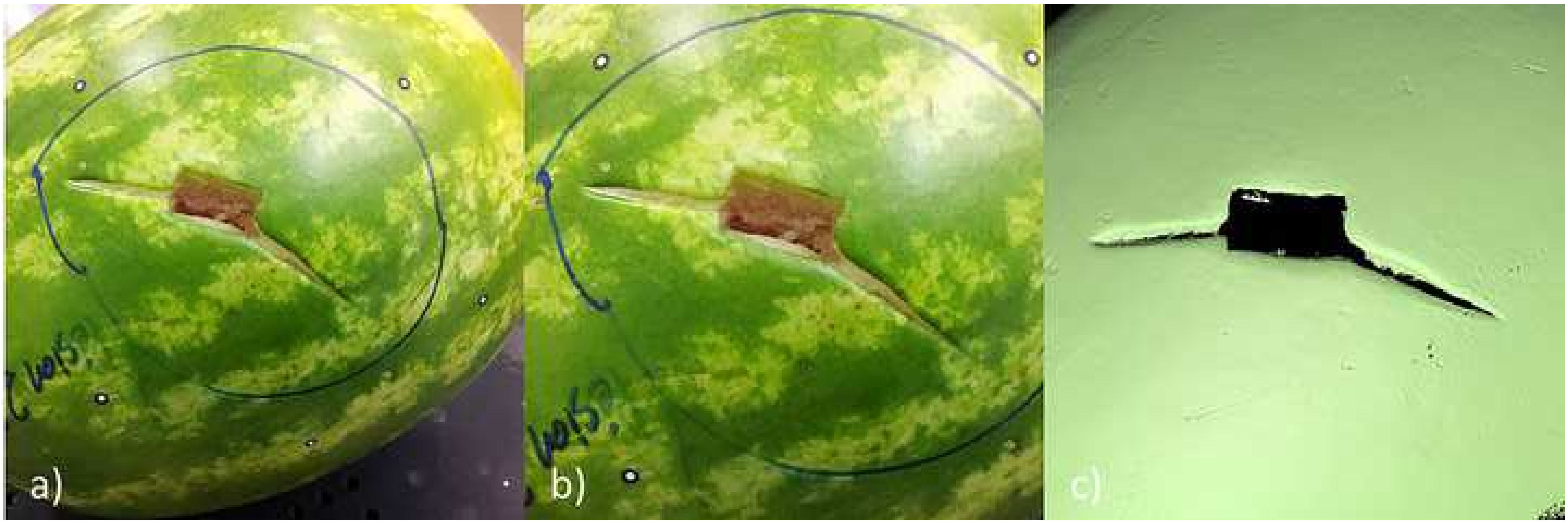
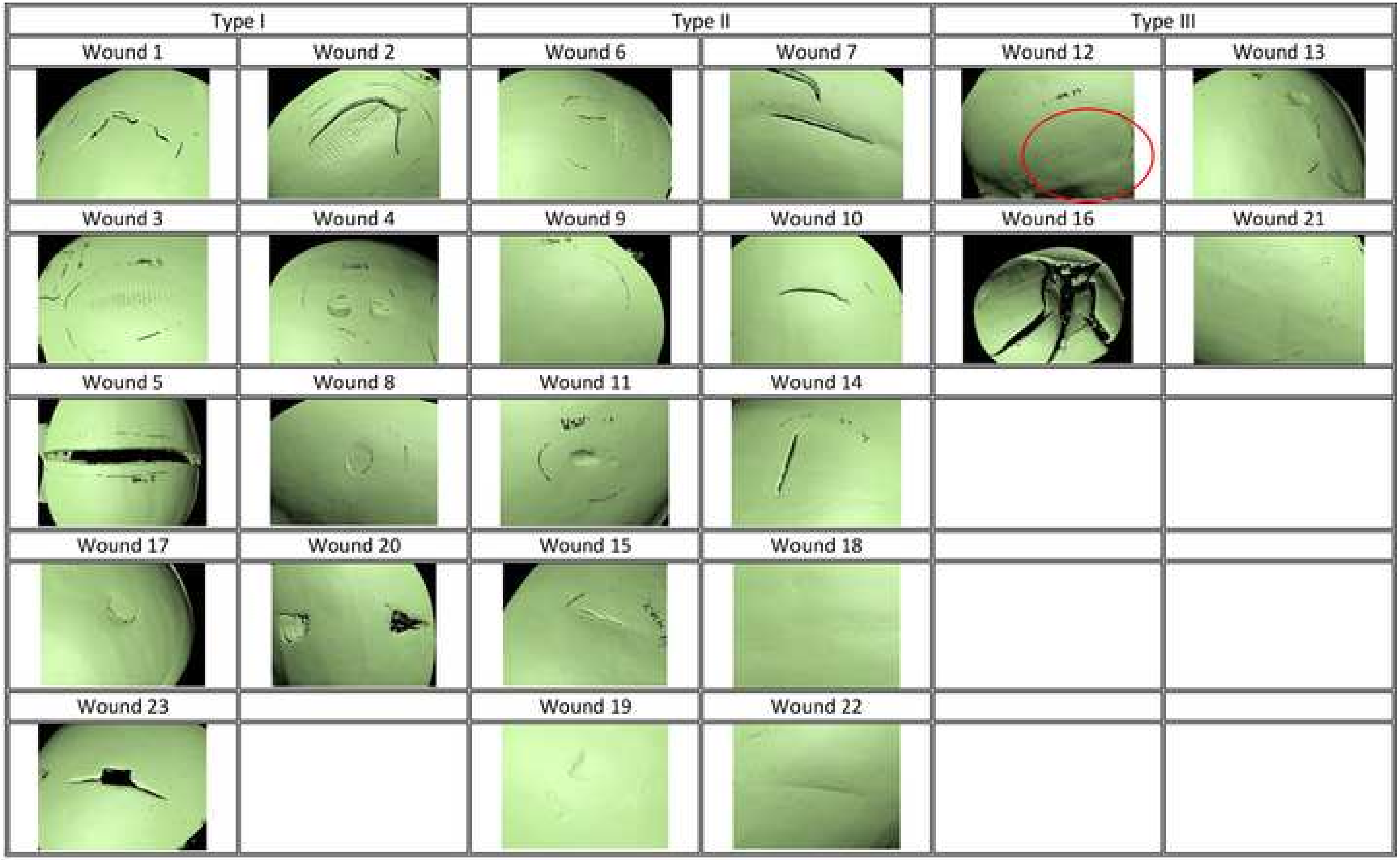


Figure 3

Figure 4


Type I
Type II
Type III
Wound 1
Wound 2
Wound 6
Wound 7
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Wound 3
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Wound 21
Wound 5
Wound 8
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Wound 22

Figure 5

Click here to access/download;Figure;Figure 5 - 129mm.jpg

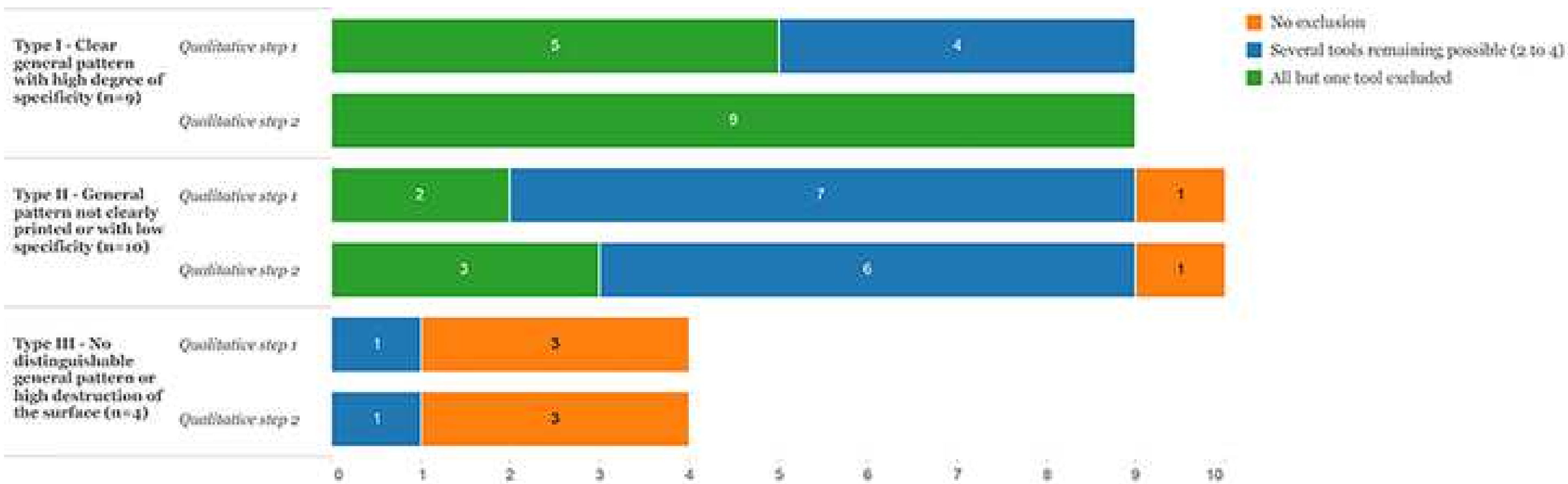

Figure 6

Click here to access/download;Figure;Figure 6 - 84mm.jpg

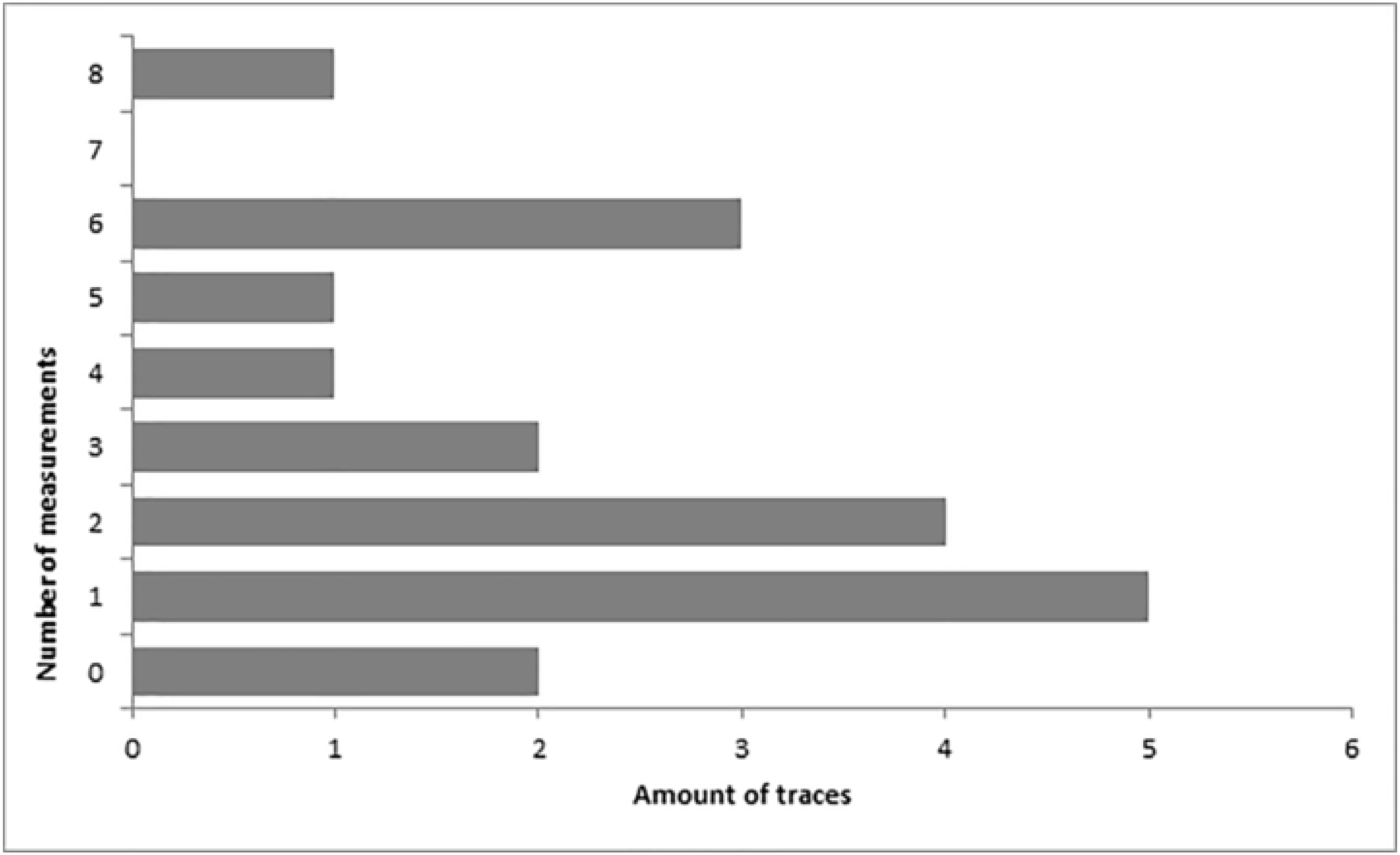

Figure 7