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

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Abstract:	<p>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.</p> <p>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.</p> <p>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.</p> <p>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.</p> <p>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.</p>

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2 **injury with its causing instrument**

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26 technique, ensuing needs and possible paths for improvement are also expounded.

27

28

29 **Keywords**

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

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37 Introduction

38 During the last decade of the 20th century, the improvement of digital photography [\[1,2\]](#) and
39 imaging techniques enabled the proliferation of solutions to record 3D data through the use of digital
40 photogrammetry and lasergrammetry [\[3-7\]](#). In legal medicine, especially in forensic traumatology,
41 another alternative of optical scanning device, mainly known as 3D surface scanning, was then put
42 forward for the three-dimensional analysis of the volumetric adequacy of a wound and a possible
43 injury-causing instrument [\[8\]](#). The contribution of 3D surface scanning instrumentation was mainly
44 emphasised through specific applications, mostly in combination with other non-invasive imaging
45 techniques such as MDCT (multi-detector computed tomography) [\[9-13\]](#) or MRI (magnetic resonance
46 imaging) [\[10,12,13\]](#). These specific applications were shown by case examples, mostly cases of traffic
47 accident reconstructions [\[4,5\]](#), comparisons of wounds with the injury-causing instrument
48 [\[3,14,15,6,16,7\]](#), and event scenario assessments [\[4,5\]](#). Several related case reports praised the high
49 quality of the images and other general advantages of the 3D surface scanning techniques, such as an
50 objective and non-invasive 3D documentation, the high resolution and the accuracy [\[4,17,8\]](#).

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

63 The present study was focussed on the use of 3D surface scanning technique for the general process
64 of comparison between a mark – representing a wound – and an object. In some other fields in
65 forensic science, a methodological approach, called ACE-V (Analysis, Comparison, Evaluation and
66 Verification), is used for the study and comparison of traces [\[20,21\]](#). The procedure followed in our
67 study was inspired by this ACE-V process. We did not claim to setup a complete and systematic study,
68 but to implement an experimental design that could unveil the pitfalls of a subjective comparison
69 made from 3D data. The purpose was to explore the ability of an operator, by means of 3D surface

70 scanning, to take a decision on the association/exclusion of an incriminated tool as the source of a
71 mock wound. Ideally, the operator was told to try to attribute the mark to one specific object. On the
72 basis of the results of this exploratory set of experiments, we tried to delineate a possible
73 methodology that could overcome the highlighted limitations. To our point of view, such a
74 methodology should encompass several sequential steps that should be clearly defined and
75 formalised, following the ACE-V approach: the description of wound, the analysis of its informational
76 content, the comparison with a reference trace made by an instrument, and the assessment of the
77 value of this comparison.

78

79 **Material and Methods**

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

85

86 **Specimens' preparation**

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

91 Twenty-three marks, referred as 'mock wounds', were produced by seven different persons striking
92 the surface of watermelons (average length between 20 and 25 cm and average diameter of
93 approximately 20 cm) with the fifteen instruments, at least one and maximum twice per tool. This
94 way of wound production was chosen because it results in a realistic blunt force trauma pattern, and
95 that it was not aimed to compare wounds with each other. On each watermelon, three or four
96 wounds were made, using two or three tools. Each watermelon, each wound as well as each tool was
97 individually labelled. After the production of a mock wound, the person that produced it, filled in a
98 so-called 'lesion protocol' with all the details related to the tool used and conditions of mark
99 production. The seven volunteers who hit the watermelons were 3 women and 4 men aged between
100 29 and 64 years old. No specific rules were given to them, just to strike the watermelons as they

101 would hurt somebody. This phase took place indoor, in the autopsy room. The main researcher in
102 charge of the study did not take part to this production phase of mock wounds, nor was she
103 informed about which tool was used to produce each of the marks.

104

105 **3D data acquisition: from scanning to modelling**

106 3D surface measurement was processed through a non-contact optical 3D digitising system Gom
107 ATOS Compact Scan 5M (Gom, Braunschweig, Germany)(Figure 1), which allows to obtain 3D models
108 from real data with high resolution and accuracy. The functioning of this scanner relies on the fringe
109 pattern projection (blue light) of adapting array of stripes that impact the surface to be measured.
110 Two 5-million-pixels cameras record the deflections of the stripes induced on the shape of the
111 surface. By triangulation principle, the measurements from both cameras are merged in a point
112 cloud representing the surface, with high resolution and accuracy. [22,23]. Acquisition was controlled
113 through the ATOS Professional V7.5 SR2 software package, also used for some further treatments in
114 conjunction with a 3ds Max 2013 software. Two different measuring volumes (MV) – corresponding
115 to different pairs of camera lenses – were used on the scanner depending on the size of the object:
116 MV 150 (resolution up to 0.062 mm) and MV 300 (resolution up to 0.124 mm). This required in
117 accordance the use of two different calibration panels: CP40/MV170 and CP40/MV320.



118

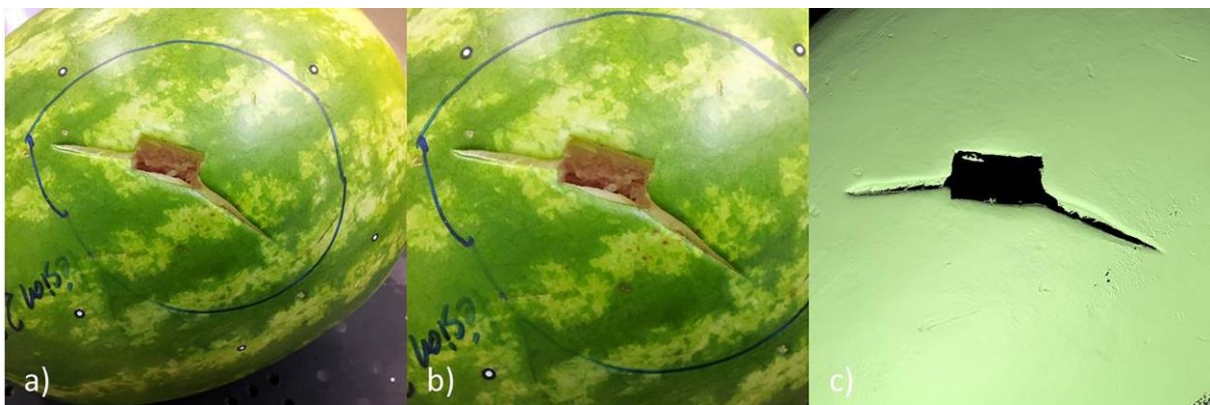
119 *Figure 1 – Gom ATOS Compact Scan 5M*

120 A calibration of the scanner was regularly carried out during the period of scanning, and in particular
121 every time the measuring volume was changed in order to assure minimal deviation in
122 measurements. Markers were placed around the mock wounds, on the surfaces of the tools as well
123 as on the support of the tools. Mock wounds and tools were scanned in a room at ambient
124 temperature (around 21°C) under controlled and stable luminosity. Parasite movements were
125 reduced to a minimum level by fixing the different parts of the camera to a tripod and by working in

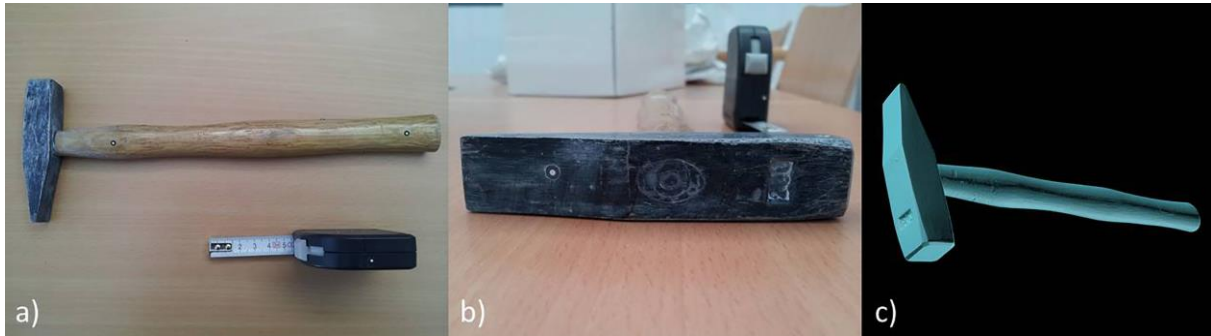
126 an isolated room. Objects whose surfaces were too shiny or dark were first sprayed with a solution of
127 titanium dioxide (TiO₂) powder in ethanol, to reduce gloss and prevent the production of artefacts.

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

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



143
144 *Figure 2 - Example of a scanned lesion. a)-b) Photographs of lesion 23 on the watermelon; c) 3D*
145 *model of lesion 23 obtained from the GOM scanner*



146

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

149

150 **Qualitative analysis and comparison**

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

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

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

165 Then, a *qualitative comparison* took place for each trace, taking sequentially into account each of the
166 considered tools. This qualitative approach included two dimensions: 1) the direct comparison of the
167 general features and particularities observed during the analysis phase, and 2) the superimposition
168 of the 3D models of the object and the trace, this latter being common practice in most of the case
169 report publications. Starting from the characteristics of a mark, observed during the analysis phase, a
170 confrontation was successively made with the features of each tool. On this basis, the main operator

171 processed to the exclusion of the tools whose features were assessed as significantly different from
172 the characteristics of the mark. Then, a qualitative concordance between the mark and the non-
173 excluded tools was considered by superimposition of the 3D models: the models of the tool were put
174 in touch with the model of the mock wound and if the positioning of both models did not show any
175 correspondence of the general characteristics (shape and dimensions), the tool was excluded as
176 possibly being at the origin of the trace.

177

178 **Quantitative comparison: measurements**

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

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

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

202 evaluation of the overall methodology and to the formulation of paths for methodological
203 improvements.

204

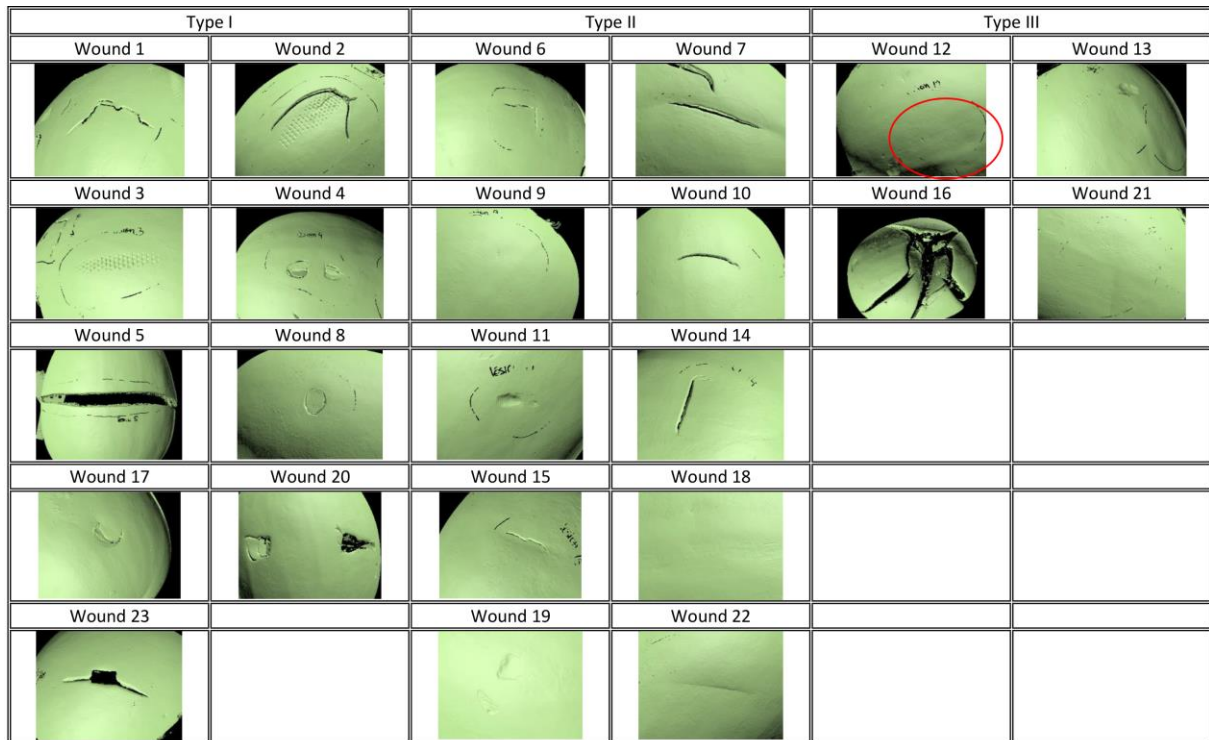
205 **Results**

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

<i>Group</i>	<i>Quality / specificity</i>	<i># of traces</i>
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

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

213



214
215 *Figure 4 - 3D models of the 23 wounds dispersed in the 3 groups. (red circle : wound location)*

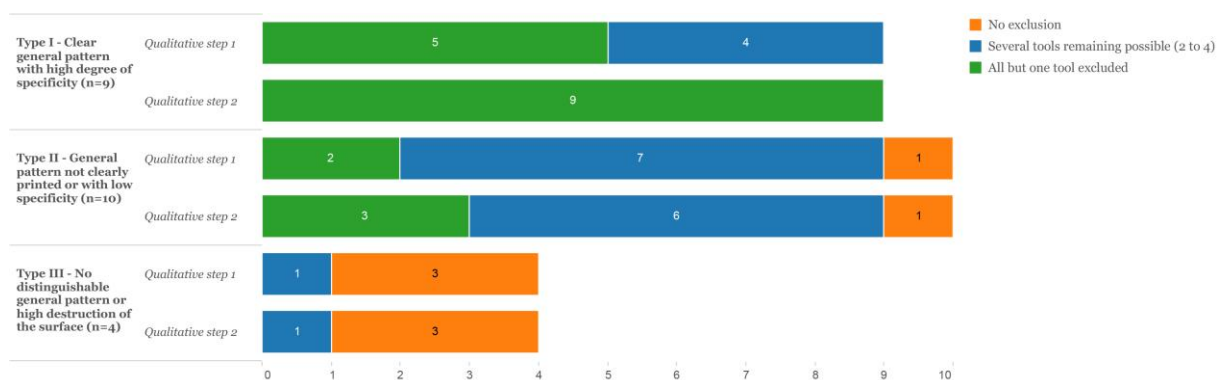
216 The two dimensions process of qualitative comparison – considering both, the adequacy of the
 217 general features between a trace and a tool – and the following superimposition of their 3D models
 218 led to 3 situations. *a) exclusion of all but on.* For 12 mock wounds, all but one of the 15 tools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

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

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

226

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

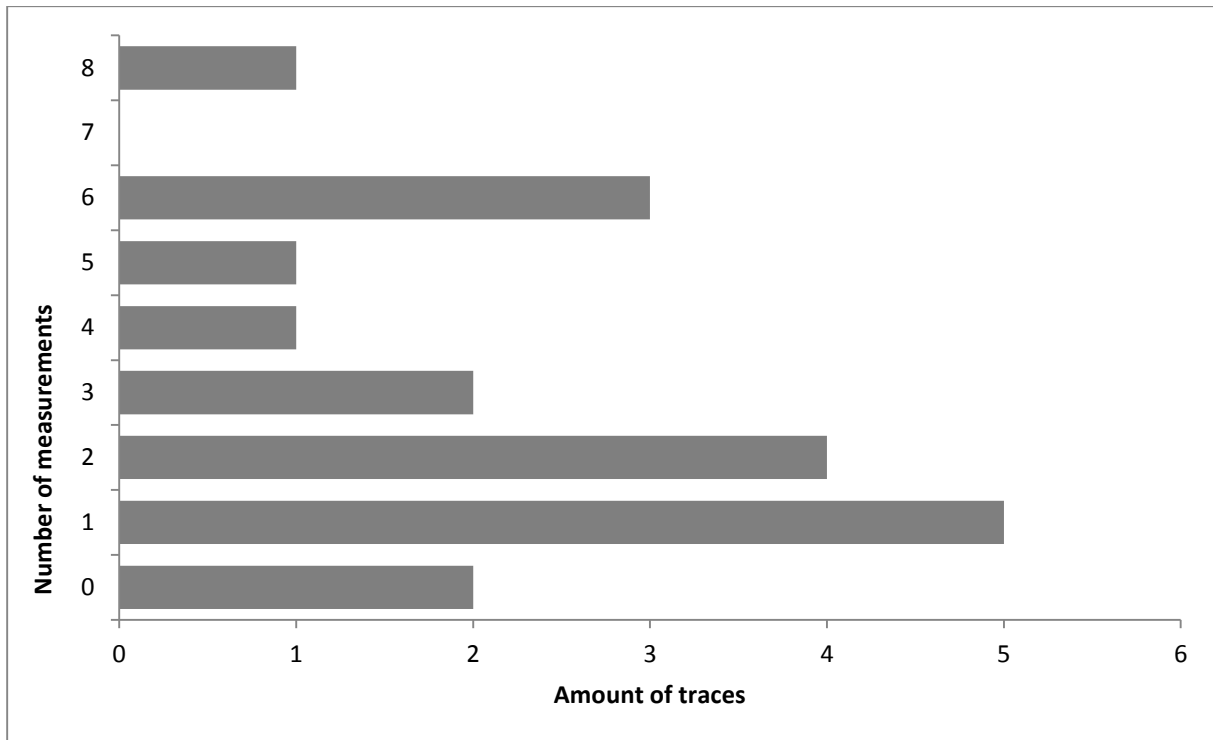


235

236 *Figure 5 – Results from the analysis and the qualitative comparison*

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

242



243

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

246

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

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

260

261

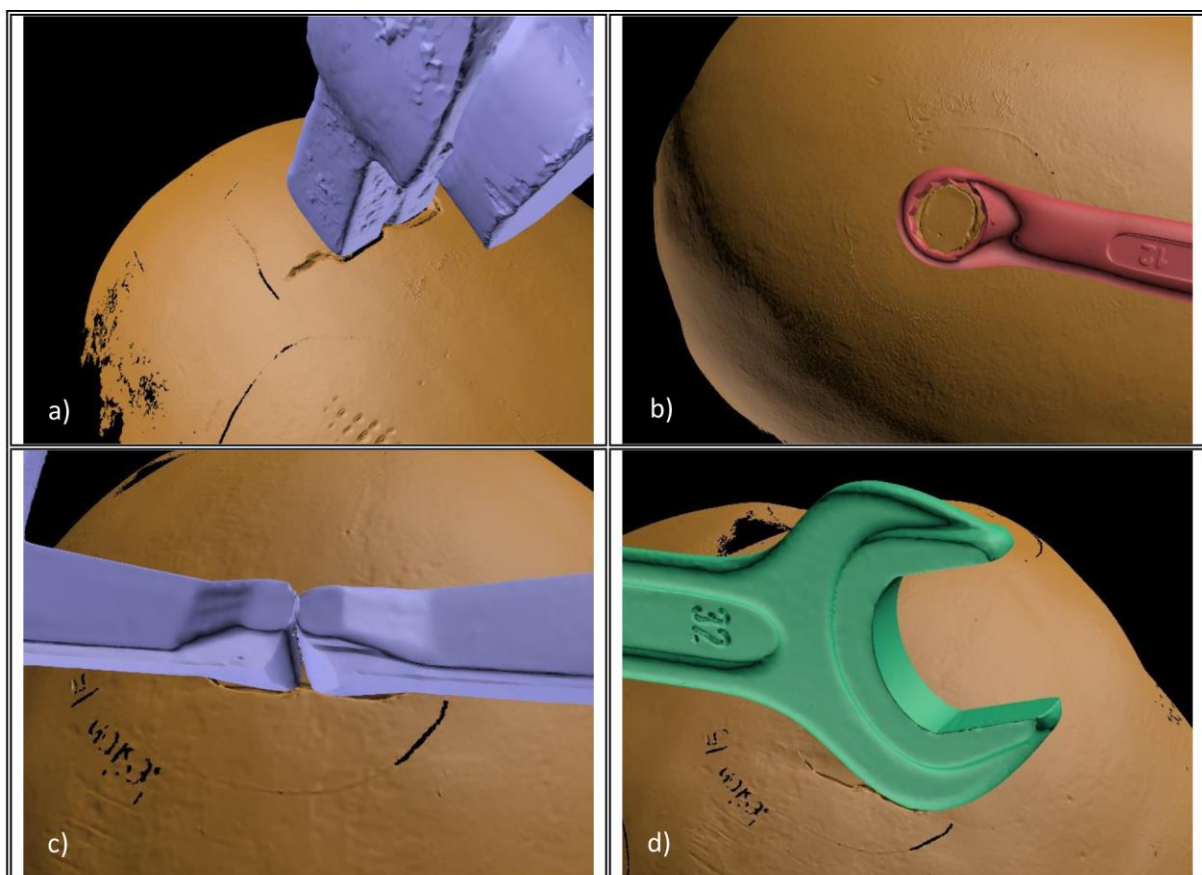
262 **Confrontation of the results obtained by the qualitative comparison with the lesion protocol**

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

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

270

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



277

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

282

283 Considering these results in the light of the degree of information of the mark, assessed during the
 284 analysis phase, was very informative. Type I group was only composed of wounds for which only the
 285 right object was not excluded. Type III group was composed of 3 wounds for which no object could
 286 be excluded and one wound for which the object was wrongly excluded by superimposition. Type II
 287 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

288

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

293

294 **Discussion**

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

302 Our study provided a first assessment of the sensibility and specificity of the comparison process
 303 between a wound and a tool through the use of 3D models obtained by surface scanning. In an
 304 overarching perspective, the results show a significant number of wrong correlations that let us
 305 foresee that the process is not reliable enough for a systematic application in routine. But

306 considering the different steps in detail, more optimistic conclusions can be drawn. These results
307 have highlighted the crucial importance of an *analysis* step in 1) describing and assessing the
308 information that can be obtained on a lesion in the perspective of a comparison process, and 2)
309 setting the limits of the possible outcomes of a comparison process. This *analysis* phase appears as
310 an imperative step before any comparison in order to prevent misinterpretations, false positives or
311 over-determination in conclusion.

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

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

330 The different steps of this study were inspired by the ACE-V (Analysis, Comparison, Evaluation, and
331 Verification) methodology that was first proposed for the friction ridge analysis (fingermarks, palm
332 marks, footmarks) [20,21] and has been extended to other morphological traces in forensic science
333 (tire tracks, tool prints, biological stains, documents, firearms, etc.). Even though our study relies on a
334 rudimentary application of the ACE-V methodology, it nevertheless highlights foreseeable benefits of
335 a thorough application of the methodology as a framework for morphological comparisons based on
336 3D models. On the basis of the information conveyed in the published articles related to comparisons
337 of 3D models, that rely on reporting successful single cases, we understand that there is no agreed
338 and reliable methodology that allows to evaluate the results of the comparison process and assess its

339 meaning value (often presented as very convincing and probative in the aforementioned papers). In
340 our study, we showed that the comparison process could lead to unsuccessful results, and even to
341 false positive conclusion, emphasising the need to anchor the comparison process in a robust
342 methodological framework. In our opinion, it is important to study in detail the benefits and
343 limitations of 3D morphological comparison process based on surface scanning models. Some
344 welcome initiatives have been made in this perspective [\[26,15,18\]](#), but unfortunately too few to use
345 the existing literature for supporting these scientific methods.

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

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

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

371

372 **Conclusion**

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

383

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

385

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468

469

470

29 **Abstract**

30 3D surface scanning is a technique brought forward for wound documentation and analysis in order
31 to identify injury-causing tools in legal medicine and forensic science. Although many case reports
32 have been published, little is known about the methodology employed by the authors.

33

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

39

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

44

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

47

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

52

53

54 **Keywords**

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

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64 **Introduction**

65 During the last decade of the 20th century, the improvement of digital photography [\[1,2\]](#) and
66 imaging techniques enabled the proliferation of solutions to record 3D data through the use of digital
67 photogrammetry and lasergrammetry [\[3-7\]](#). In legal medicine, especially in forensic traumatology,
68 another alternative of optical scanning device, mainly known as 3D surface scanning, was then put
69 forward for the three-dimensional analysis of the volumetric adequacy of a wound and a possible
70 injury-causing instrument [\[8\]](#). The contribution of 3D surface scanning instrumentation was mainly
71 emphasised through specific applications, mostly in combination with other non-invasive imaging
72 techniques such as MDCT (multi-detector computed tomography) [\[9-13\]](#) or MRI (magnetic resonance
73 imaging) [\[10,12,13\]](#). These specific applications were shown by case examples, mostly cases of traffic
74 accident reconstructions [\[4,5\]](#), comparisons of wounds with the injury-causing instrument
75 [\[3,14,15,6,16,7\]](#), and event scenario assessments [\[4,5\]](#). Several related case reports praised the high
76 quality of the images and other general advantages of the 3D surface scanning techniques, such as an
77 objective and non-invasive 3D documentation, the high resolution and the accuracy [\[4,17,8\]](#).

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

90 The present study was focussed on the use of 3D surface scanning technique for the general process
91 of comparison between a mark – representing a wound – and an object. In some other fields in
92 forensic science, a methodological approach, called ACE-V (Analysis, Comparison, Evaluation and
93 Verification), is used for the study and comparison of traces [\[20,21\]](#). The procedure followed in our
94 study was inspired by this ACE-V process. We did not claim to setup a complete and systematic study,
95 but to implement an experimental design that could unveil the pitfalls of a subjective comparison
96 made from 3D data. The purpose was to explore the ability of an operator, by means of 3D surface

97 scanning, to take a decision on the association/exclusion of an incriminated tool as the source of a
98 mock wound. Ideally, the operator was told to try to attribute the mark to one specific object. On the
99 basis of the results of this exploratory set of experiments, we tried to delineate a possible
100 methodology that could overcome the highlighted limitations. To our point of view, such a
101 methodology should encompass several sequential steps that should be clearly defined and
102 formalised, following the ACE-V approach: the description of wound, the analysis of its informational
103 content, the comparison with a reference trace made by an instrument, and the assessment of the
104 value of this comparison.

105

106 **Material and Methods**

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

112

113 **Specimens' preparation**

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

118 Twenty-three marks, referred as 'mock wounds', were produced by seven different persons striking
119 the surface of watermelons (average length between 20 and 25 cm and average diameter of
120 approximately 20 cm) with the fifteen instruments, at least one and maximum twice per tool. This
121 way of wound production was chosen because it results in a realistic blunt force trauma pattern, and
122 that it was not aimed to compare wounds with each other. On each watermelon, three or four
123 wounds were made, using two or three tools. Each watermelon, each wound as well as each tool was
124 individually labelled. After the production of a mock wound, the person that produced it, filled in a
125 so-called 'lesion protocol' with all the details related to the tool used and conditions of mark
126 production. The seven volunteers who hit the watermelons were 3 women and 4 men aged between
127 29 and 64 years old. No specific rules were given to them, just to strike the watermelons as they

128 would hurt somebody. This phase took place indoor, in the autopsy room. The main researcher in
129 charge of the study did not take part to this production phase of mock wounds, nor was she
130 informed about which tool was used to produce each of the marks.

131

132 **3D data acquisition: from scanning to modelling**

133 3D surface measurement was processed through a non-contact optical 3D digitising system Gom
134 ATOS Compact Scan 5M (Gom, Braunschweig, Germany)(Figure 1), which allows to obtain 3D models
135 from real data with high resolution and accuracy. The functioning of this scanner relies on the fringe
136 pattern projection (blue light) of adapting array of stripes that impact the surface to be measured.
137 Two 5-million-pixels cameras record the deflections of the stripes induced on the shape of the
138 surface. By triangulation principle, the measurements from both cameras are merged in a point
139 cloud representing the surface, with high resolution and accuracy. [22,23]. Acquisition was controlled
140 through the ATOS Professional V7.5 SR2 software package, also used for some further treatments in
141 conjunction with a 3ds Max 2013 software. Two different measuring volumes (MV) – corresponding
142 to different pairs of camera lenses – were used on the scanner depending on the size of the object:
143 MV 150 (resolution up to 0.062 mm) and MV 300 (resolution up to 0.124 mm). This required in
144 accordance the use of two different calibration panels: CP40/MV170 and CP40/MV320.



145

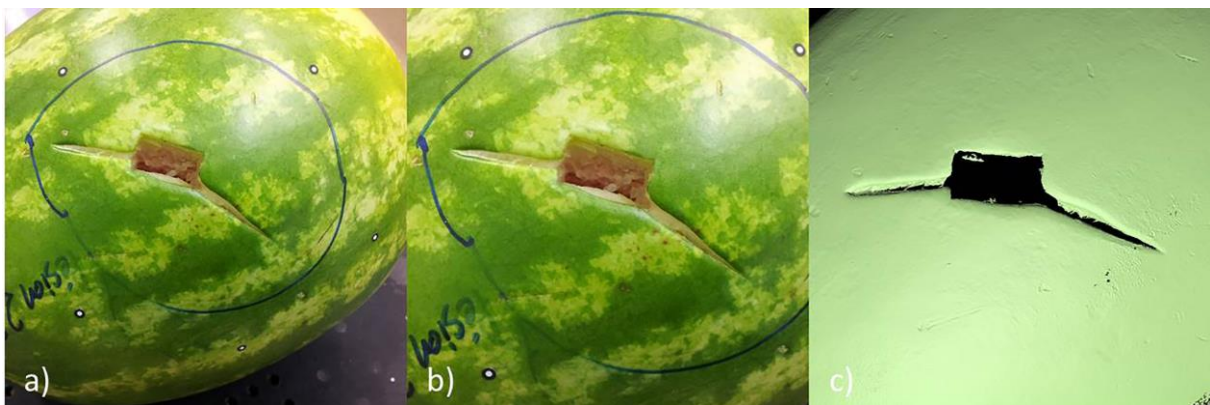
146 *Figure 1 – Gom ATOS Compact Scan 5M*

147 A calibration of the scanner was regularly carried out during the period of scanning, and in particular
148 every time the measuring volume was changed in order to assure minimal deviation in
149 measurements. Markers were placed around the mock wounds, on the surfaces of the tools as well
150 as on the support of the tools. Mock wounds and tools were scanned in a room at ambient
151 temperature (around 21°C) under controlled and stable luminosity. Parasite movements were
152 reduced to a minimum level by fixing the different parts of the camera to a tripod and by working in

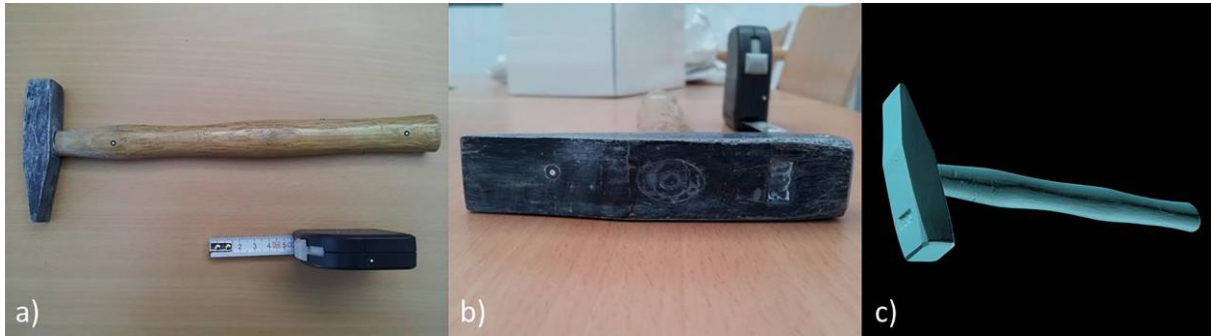
153 an isolated room. Objects whose surfaces were too shiny or dark were first sprayed with a solution of
154 titanium dioxide (TiO₂) powder in ethanol, to reduce gloss and prevent the production of artefacts.

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

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



170
171 *Figure 2 - Example of a scanned lesion. a)-b) Photographs of lesion 23 on the watermelon; c) 3D*
172 *model of lesion 23 obtained from the GOM scanner*



173

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

176

177 **Qualitative analysis and comparison**

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

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

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

192 Then, a *qualitative comparison* took place for each trace, taking sequentially into account each of the
193 considered tools. This qualitative approach included two dimensions: 1) the direct comparison of the
194 general features and particularities observed during the analysis phase, and 2) the superimposition
195 of the 3D models of the object and the trace, this latter being common practice in most of the case
196 report publications. Starting from the characteristics of a mark, observed during the analysis phase, a
197 confrontation was successively made with the features of each tool. On this basis, the main operator

198 processed to the exclusion of the tools whose features were assessed as significantly different from
199 the characteristics of the mark. Then, a qualitative concordance between the mark and the non-
200 excluded tools was considered by superimposition of the 3D models: the models of the tool were put
201 in touch with the model of the mock wound and if the positioning of both models did not show any
202 correspondence of the general characteristics (shape and dimensions), the tool was excluded as
203 possibly being at the origin of the trace.

204

205 **Quantitative comparison: measurements**

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

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

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

229 evaluation of the overall methodology and to the formulation of paths for methodological
230 improvements.

231

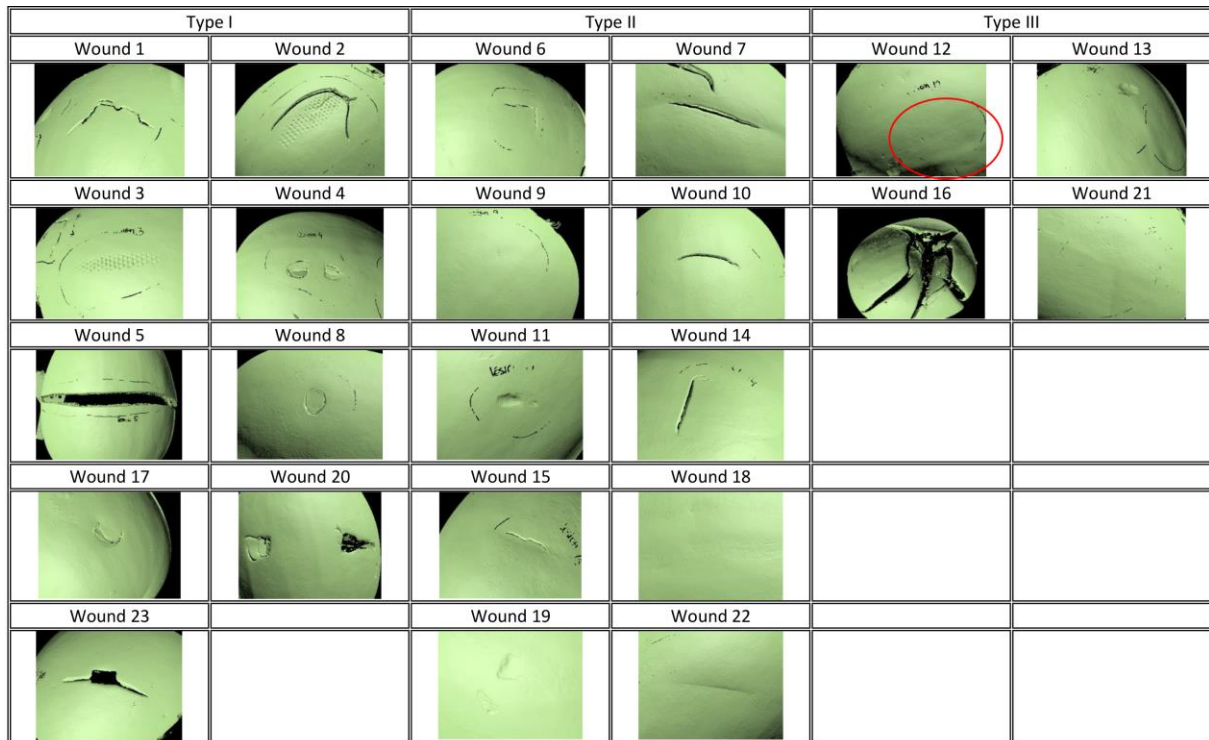
232 **Results**

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

<i>Group</i>	<i>Quality / specificity</i>	<i># of traces</i>
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

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

240



241
242 *Figure 4 - 3D models of the 23 wounds dispersed in the 3 groups. (red circle : wound location)*

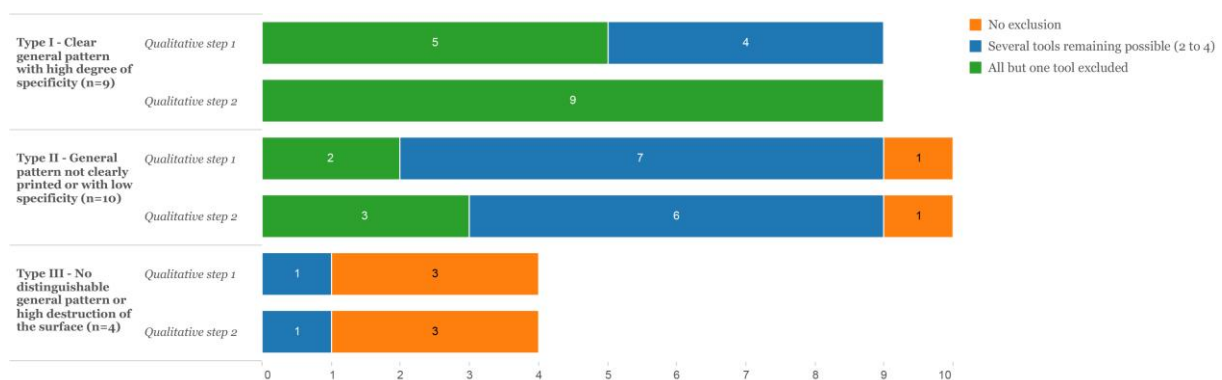
243 The two dimensions process of qualitative comparison – considering both, the adequacy of the
244 general features between a trace and a tool – and the following superimposition of their 3D models
245 led to 3 situations. *a) exclusion of all but on.* For 12 mock wounds, all but one of the 15 tools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

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

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

253

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

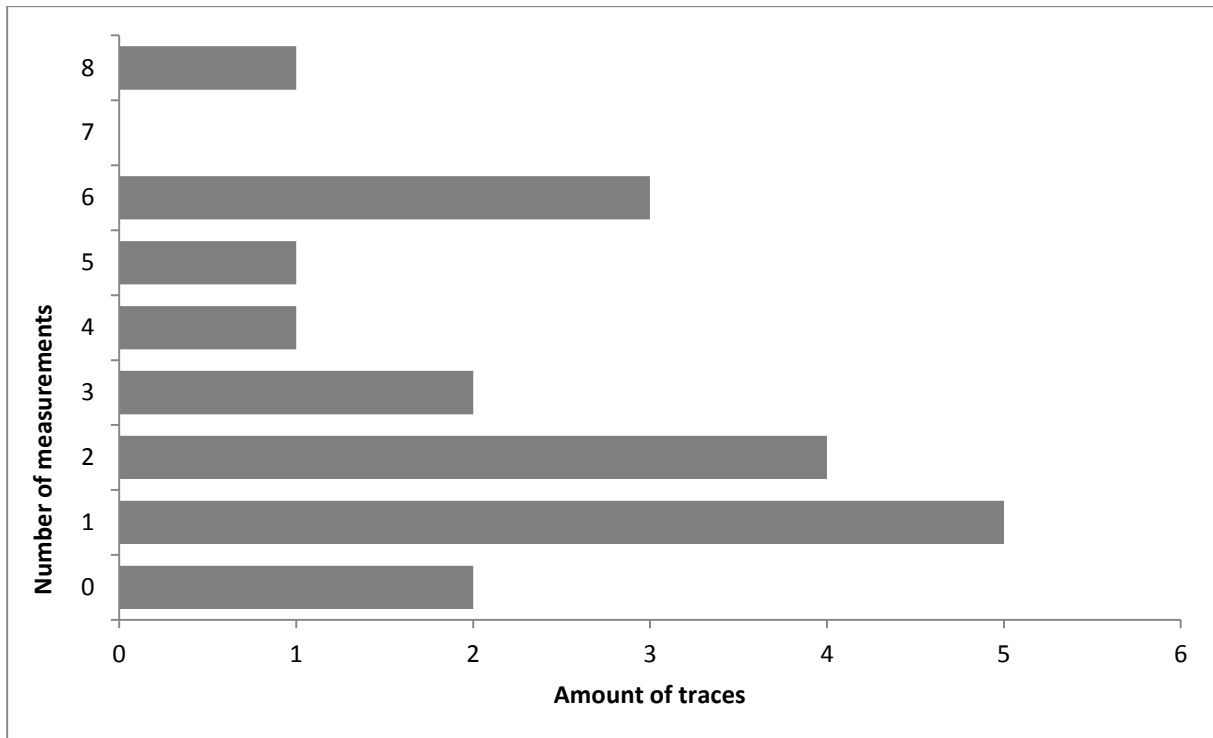


262

263 *Figure 5 – Results from the analysis and the qualitative comparison*

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

269



270

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

273

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

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

287

288

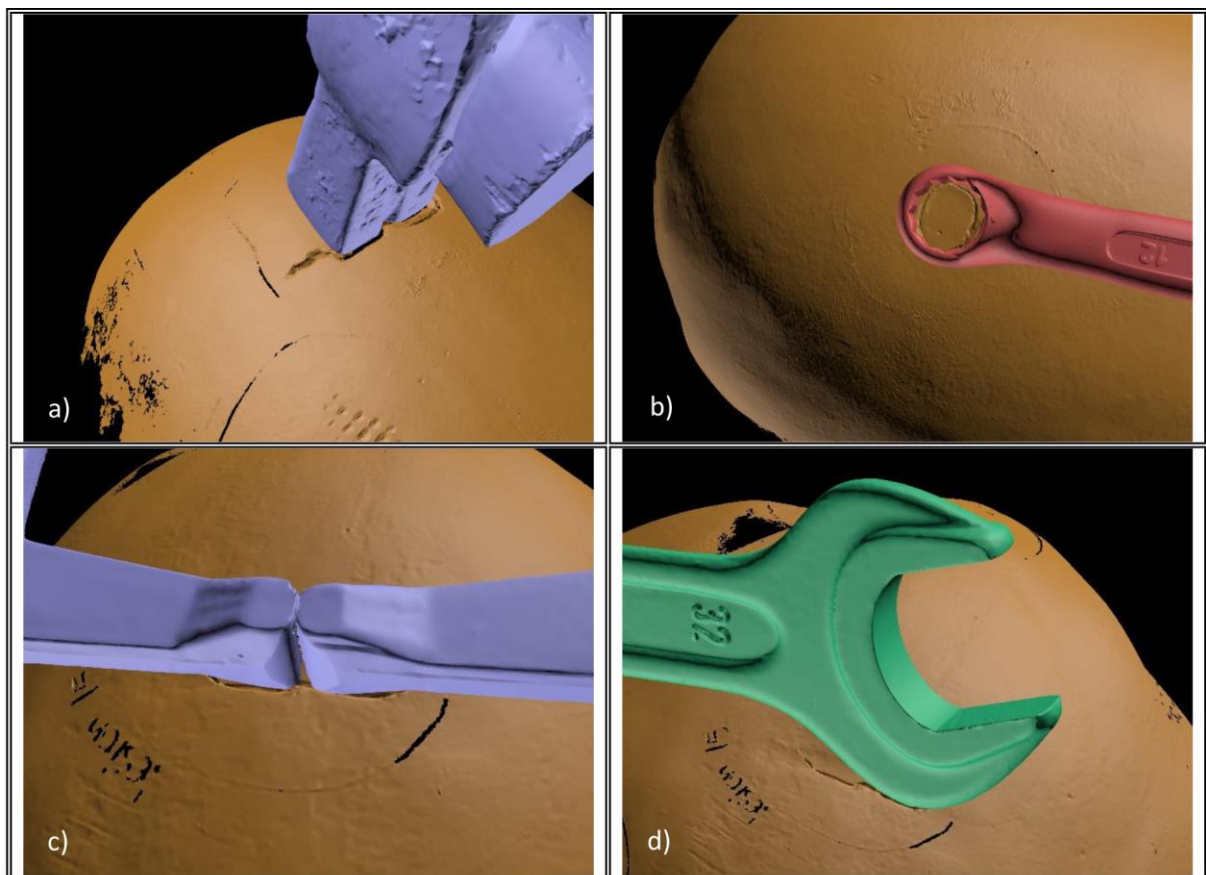
289 **Confrontation of the results obtained by the qualitative comparison with the lesion protocol**

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

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

297

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



304

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

309

310 Considering these results in the light of the degree of information of the mark, assessed during the
 311 analysis phase, was very informative. Type I group was only composed of wounds for which only the
 312 right object was not excluded. Type III group was composed of 3 wounds for which no object could
 313 be excluded and one wound for which the object was wrongly excluded by superimposition. Type II
 314 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

315

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

320

321 **Discussion**

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

329 Our study provided a first assessment of the sensibility and specificity of the comparison process
 330 between a wound and a tool through the use of 3D models obtained by surface scanning. In an
 331 overarching perspective, the results show a significant number of wrong correlations that let us
 332 foresee that the process is not reliable enough for a systematic application in routine. But

333 considering the different steps in detail, more optimistic conclusions can be drawn. These results
334 have highlighted the crucial importance of an *analysis* step in 1) describing and assessing the
335 information that can be obtained on a lesion in the perspective of a comparison process, and 2)
336 setting the limits of the possible outcomes of a comparison process. This *analysis* phase appears as
337 an imperative step before any comparison in order to prevent misinterpretations, false positives or
338 over-determination in conclusion.

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

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

357 The different steps of this study were inspired by the ACE-V (Analysis, Comparison, Evaluation, and
358 Verification) methodology that was first proposed for the friction ridge analysis (fingermarks, palm
359 marks, footmarks) [20,21] and has been extended to other morphological traces in forensic science
360 (tire tracks, tool prints, biological stains, documents, firearms, etc.). Even though our study relies on a
361 rudimentary application of the ACE-V methodology, it nevertheless highlights foreseeable benefits of
362 a thorough application of the methodology as a framework for morphological comparisons based on
363 3D models. On the basis of the information conveyed in the published articles related to comparisons
364 of 3D models, that rely on reporting successful single cases, we understand that there is no agreed
365 and reliable methodology that allows to evaluate the results of the comparison process and assess its

366 meaning value (often presented as very convincing and probative in the aforementioned papers). In
367 our study, we showed that the comparison process could lead to unsuccessful results, and even to
368 false positive conclusion, emphasising the need to anchor the comparison process in a robust
369 methodological framework. In our opinion, it is important to study in detail the benefits and
370 limitations of 3D morphological comparison process based on surface scanning models. Some
371 welcome initiatives have been made in this perspective [\[26,15,18\]](#), but unfortunately too few to use
372 the existing literature for supporting these scientific methods.

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

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

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

398

399 **Conclusion**

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

410

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

412

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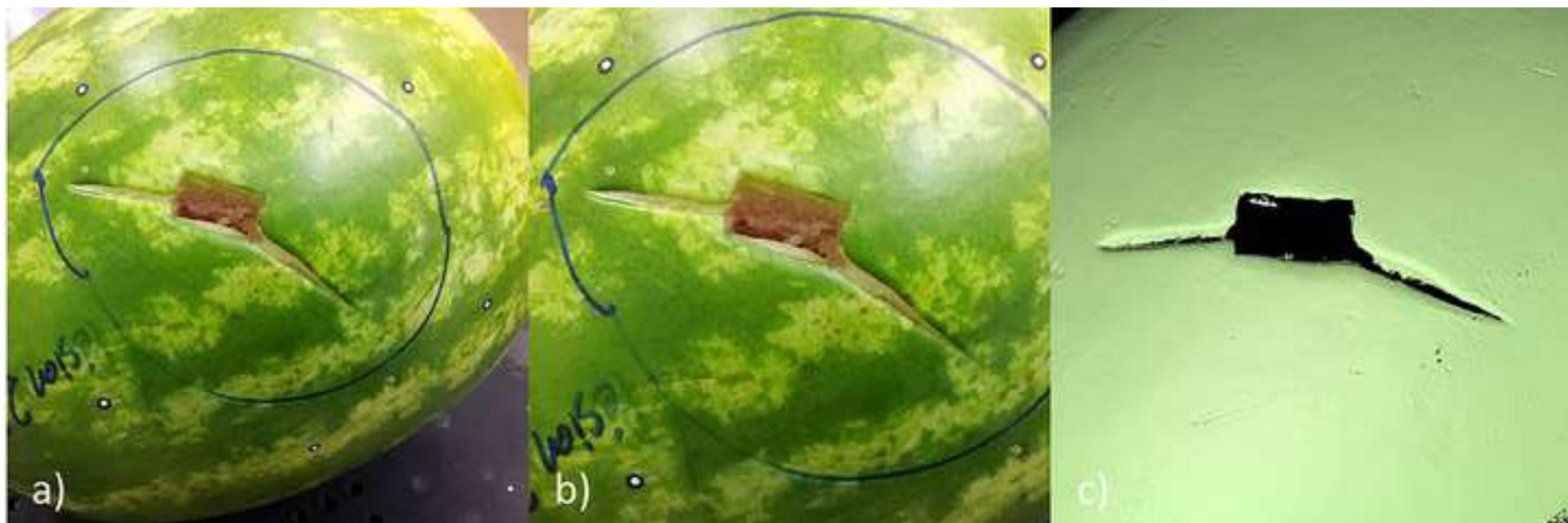
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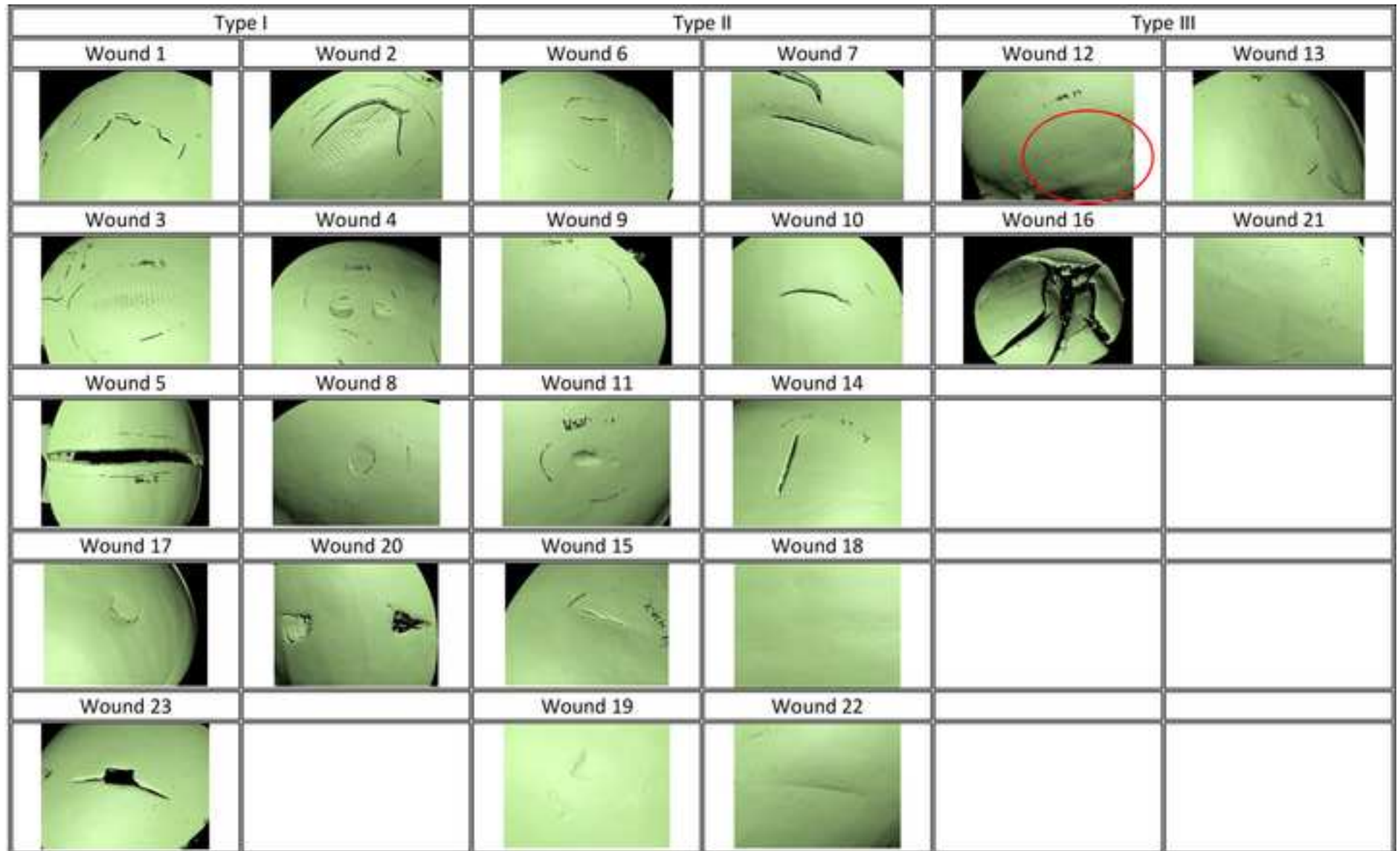


Figure 5

