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Giovanna Sansoni,[1] B.E.; Cristina Cattaneo,[2] Ph.D., M.D.; Marco Trebeschi,[1] B.E.; Daniele Gibelli,[2] M.D.; Davide Porta,[2] B.S.; and Massimo Picozzi,[3] M.D.

Feasibility of Contactless 3D Optical Measurement for the Analysis of Bone and Soft Tissue Lesions: New Technologies and Perspectives in Forensic Sciences

ABSTRACT: In forensic pathology and anthropology, a correct analysis of lesions on soft tissues and bones is of the utmost importance, in order to verify the cause and manner of death. Photographs, videos, and photogrammetry may be an optimal manner of immortalizing a lesion, both on cadavers and skeletal remains; however, none of these can supply a detailed three-dimensional (3D) modeling of the lesion. Up to now, only the use of casts has given us the possibility of studying deep lesions such as saw marks with an accurate and complete 3D reconstruction of bone structure. The present study aims at verifying the applicability of 3D optical contactless measurement for the accurate recording of soft tissue and bone lesions, in order to develop a unique and precise method of registering and analyzing lesions, both in forensic pathology and anthropology. Three cases were analyzed: the first, a car accident with blunt force skin injuries; the second, a murder with blunt force injury to the head applied with a metal rod; the third, a series of sharp force knife and saw lesions on bone. Results confirm that 3D optical digitizing technology is a crucial tool in the immortalization of wound morphology in the medico-legal context even on "difficult" substrates such as cut marks and saw marks on bone.

KEYWORDS: forensic science, soft tissues, bones, blunt lesions, sharp lesions, 3D optical measurement, toolmark analysis

The most important step both at postmortem examination and in anthropological analysis is represented by the in-depth and accurate study of lesions. The analysis of lesions on soft tissues and bone can provide valid information on the shape and size of the tools used during an aggression. Therefore, a detailed 3D study on a toolmark, be it on skin or bone, is crucial. Photographs, although detailed, cannot immortalize the complexity of a lesion in all three dimensions. This may be particularly crucial at the scene of crime, where documentation becomes urgent because several days may go by before the autopsy is performed: this delay may lead to some alteration of the soft tissues and therefore of lesion morphology. Regardless however of whether one needs to immortalize the lesion at the scene of crime or at the autopsy, capturing maximum detail is fundamental. With skeletal remains, a detailed analysis of wounds such as saw marks has been performed up to now by casting only (1).

In the past years, the literature has pointed out the use of radiodiagnostic tests, such as scanning electron microscopy (SEM), to improve the quality of detail acquired on the shape and size of tools in bone lesions (2–4), although such analyses cannot be applied to the study of the environment and to larger wounds in their entirety; the availability of a technology able to measure and record the macroscopical characteristics of lesions on soft tissues, avoiding contact, in short times and with low invasiveness of the body and scene, is of the utmost importance, particularly in the case of soft tissues. Three-dimensional (3D) optical digitizers represent the last frontier in attempting to accurately capture the 3D shape of soft tissue lesions (4). These instruments have been originally developed for industrial applications (5–7). They are now largely used in other applications, as, e.g., the virtual restitution of historical monuments (8), and in the measurement and prosthetic reconstruction of body parts (9–11). They inherently produce the 3D shape of the surfaces without contact (optical beams are used1 to perform the measurement) and show good efficiency in terms of both measurement accuracy and speed (12).

They have been proposed as optimal acquisition devices instead of 3D SEM and computed tomography (CT) systems for a number of reasons: (i) they show a markedly increased speed of analysis with respect to 3D SEM and CT, because they are based on a pure-reflective approach to the measurement, and do not require slicing of the tissues, (ii) they are available on the market at by far lower costs with respect to CT/MRI systems, (iii) they show very good measurement performances in the macroscopic range, and (iv) are designed to perform the measurement in harsh conditions. Hence, they are rugged and portable and can be used on-site (i.e., directly on the crime scene and/or to analyze the victim in very short times). The 3D optical digitizers are now available on the market under three major classes, depending on the measurement range: (i) long-range instruments, (ii) medium-range instruments, and (iii) short-range instruments. Long-range systems are based on the time of flight (TOF) principle: they capture the 3D shape of very large scenes, spanning from tens of meters to some several

[1]Laboratorio di Optoelettronica, Dipartimento di Elettronica per l'Automazione, Università degli Studi di Brescia, Via Branze 38, 25123 Brescia, Italy.
[2]Laboratorio di Antropologia e Odontologia Forense (LABANOF), Istituto di Medicina Legale e delle, Assicurazioni, Università degli Studi di Milano, Via Mangiagalli 37, 20133 Milano, Italy.
[3]LIUC, Università Carlo Cattaneo, Corso Matteotti 22, 21053 Castellanza (VA), Italy.

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kilometers. Medium-range devices are based either on the TOF method or on the photogrammetric technique. They perform the measurement in ranges from a few meters to some tens of meters (13,14). Short-range instruments are based on the optical triangulation process as well as on photogrammetry (15). The measurement range spans from some centimeters to fractions of a meter. A large variety of systems belonging to this last class is now available.

Thus, in the past decade, several methods of image acquisition have been developed: photogrammetry, laser scanner plus sound sensor (16), and laser scanner (17). Actually since the early 1990s, the 3D acquiring system technology has been used in several fields of medicine; the first applications were performed in a clinical context and concerned the analysis and recording of changes in chronic wound healing (18–20). The acquisition of 3D images allow one in fact to perform an estimation of wound volume without contact of wound surface (with possible traumatization), such as casts and saline filling (21). The main advantages in using 3D image acquiring systems is the more precise estimation of the dimensions of the lesions by complete 3D lesion visualization, which is of the utmost importance in case of deep lesions as observed in chronic wounds (22). The same technologies have been used in the odontological context, particularly for the comparison of bite marks with casts from suspects (12). Although authors reported a high reliability of the method, the precision of the method was strongly influenced by the presence of specific tooth patterns and conservation of skin lesions. Moreover, DNA analysis is required in order to confirm the diagnosis (23).

The 3D image acquiring technology has been recently used in body reconstruction and modeling in virtopsy procedure: it consists in the creation of a body image in a virtual 3D space by merging information by CT and nuclear magnetic resonance (NMR) with a skin surface analysis by photogrammetry or 3D optical digitizer (24,25). The main advantages consist in reconstruction of lesions and in verifying the consistency between morphological characteristics of the wound with those of the tool used. The merging of surface information with inner viscera images by CT and NMR allows a complete analysis of lesions before the postmortem examination. Literature has pointed out the great precision and accuracy of this approach to morphological analysis of lesions both on soft tissues and bones (26).

Every 3D image acquiring system however is affected by an error rate: although the 3D laser scanner can be calibrated on a specific measurement range, the reduced error rate in acquisition is offset by the increased inaccuracy in 3D image modeling and merging. The first attempts at measuring metrical characteristics from chronic wounds pointed out an overestimation of 1 mm, with relevant modification of perimeter and area values (22). The Minolta Vivid700 3D laser scanner (12) showed a mean accuracy of 0.5 mm in vertical dimension and 0.3 mm in horizontal dimension on curved surfaces, such as a calibrated cylinder; the same tool showed a higher inaccuracy in depth measurement (0.7 mm in measurement of palatal depth) and in facial models (1.9 mm). The error rate is a crucial point in 3D image acquisition; whereas in the clinical context chronic wounds are frequently deep, with a lower impact of error in final measurement, lesions observed in forensic cases may be shallow; superficial abrasions, e.g., may have a depth <0.1 mm, and in these cases, even a slight error rate may radically weigh upon the final results. Nevertheless, the 3D technology may bring on a relevant contribution also in the forensic context.

Surprisingly, however, not many articles in the forensic literature support and confirm the use of this technology. In fact in science at times unfortunately disciplines do not always relate to each other. So 3D optics has had a fairly large development in clinical sciences but has only recently been "advertised" in forensics (23–28), and in particular very little on bone injuries. Thus the present study aims to add "substance" to the usefulness of a well-known method (3D optics) to the forensic scenario where scanty information still exists. Furthermore, blunt force and gunshot injury mainly have been approached in the previous articles. In this piece of work, cut marks and saw marks are also studied, particularly in bone.

The objective of this study was therefore to verify the feasibility of using an optical digitizer of the third class to perform the contacless 3D measurement of soft tissues and bone lesions, in order to assess a unique, precise, and reliable method of investigation useful in forensic pathology and anthropology; moreover, this study aims at stressing the usefulness of this technology in the forensic context in order to perform a reliable, fast, and complete recording of lesions and environment both in the analysis of the crime scene and at autopsy.

Materials and Methods

The instrument used to perform the acquisitions is the Vivid 910 digitizer (Konica Minolta, Inc., Osaka, Japan) (affected in this case by a mean error of 0.05 mm). The measurement principle is briefly explained in Fig. 1: a laser beam, focused by a cylindrical lens, projects a laser stripe onto the surface. The originally straight laser

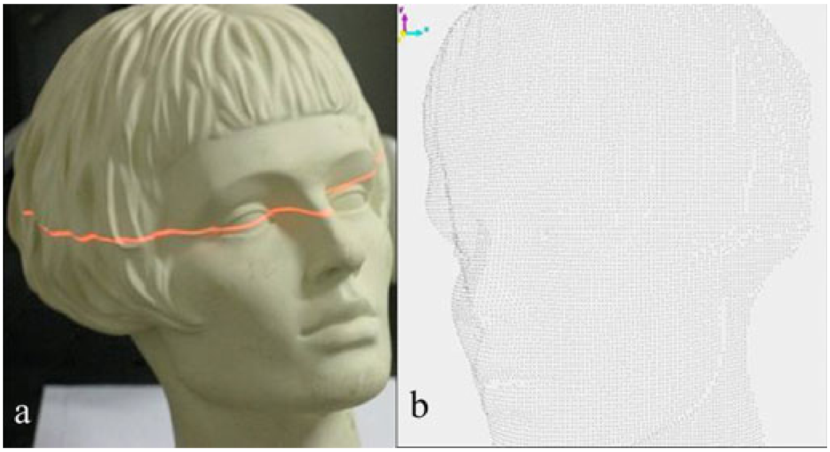

FIG. 1—*The 3D optical digitizer measurement principle. (a) The deformation of the laser stripe induced by the object shape; (b) the whole point cloud of the inspected part.*

stripe is deformed by the surface shape. This deformation is captured at an angle by a video camera (Fig. 1*a*). The acquired light stripe is elaborated by following the optical triangulation principle, which produces the 3D coordinates of the object points illuminated by the stripe. The measurement of the whole object is accomplished by scanning the scene. The resulting data sets form the so-called "point cloud," which represents the 3D shape of the target (Fig. 1*b*). The system is equipped with a RGB fotocamera, which allows the 2D recording of the color surface. As the laser source is "eye-safe," the instrument is commonly used even for other forms of laser scanning, such as facial mapping (10). Image acquisition was performed by manual segmentation. The system is rugged, portable, and extremely compact; it can be set up in three different configurations, denoted as WIDE, MIDDLE, and TELE mode, respectively. In the WIDE setup, the camera optics has a focal length of 8 mm. A typical value of the measurement area is 1 m by 1 m, the measurement range is up to 1 m, and the measurement resolution is about 0.65 mm. In the MIDDLE setup, the camera optics has a focal length of 14 mm. The acquisition area is from 600×450 mm^2 to 350×250 mm^2, the measurement range is lower than 500 mm, and the resolution is 0.3 mm. In the TELE setup, a 25-mm lens is mounted. The dimension of the acquired views spans from 250 by 190 mm^2 to 140 by 100 mm^2; the range is equal or even less than 300 mm and the resolution is 0.15 mm. The measurement time is equal to 10 sec (data storage included). The performances of the instrument can be tested by performing suitable calibration. In this way, it is always possible to ensure the referability of the measurements.

The possibility of selecting the camera optics depending on the surface dimension and the fact that the system can be easily positioned with respect to the surface are strategic for optimizing the adherence of captured data to the real lesion.

The optical digitizer is equipped with suitable software for the elaboration of the raw point clouds. The elaboration includes (i) data alignment, when multi-view acquisition is required, (ii) data sampling and noise reduction, to improve the signal to noise ratio, and (iii) the generation of suitable triangle meshes from the measured points, to obtain the topological description of the surface. The triangle meshes represent the so-called 3D models of the original surface. The 3D models give the objective description of the original lesions. They can be viewed on the computer screen by using 3D viewers and inherently yield the possibility of extracting the information of interest, in terms of point to point distances, sections, and areas. In addition, the models can be input to a stereolithographic machine for the physical reconstruction of the original surfaces (Fig. 1).

The 3D optical digitizer was applied to three forensic cases, which underwent postmortem examination or anthropological analysis. The first case refers to a car accident, with production of different abrasions on lower limbs (Fig. 2); the second case concerns a woman who died after blunt force injury applied with a metal rod on the head (Fig. 3); in the third case, a femur with several knife and saw marks was analyzed (Fig. 4).

The lesions described above were gauged by means of the Vivid 910 digitizer. The resulting point clouds were suitably elaborated in order to create the corresponding 3D models. Moreover, in the second case, a comparison between the acquired skin lesion and a 3D model of the metallic pipe which was supposed to have been used by the murderer was performed.

FIG. 2—*Case 1: the abrasions on the right thigh from the car accident.*

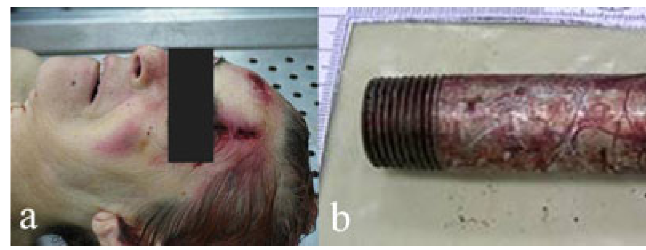

FIG. 3—*Case 2: (a) the head wounds and lacerations; (b) the metallic rod presumed to be the tool used during the aggression.*

FIG. 4—*Case 3: cut marks and saw marks on the right femur.*

Results

In the case of the car accident, the analysis of the abrasions observed during the postmortem examination was aimed at verifying the significance of the physical measurements and the possibility of acquiring shape, depth, and outline from visible skin lesions. Because of the small size of the lesions, the instrument was set up in the short-range configuration (TELE mode). Figure 5*a* shows the 3D model corresponding with the skin surface in Fig. 2. Here, the color pattern acquired by the RGB fotocamera has been superimposed to the shape information. The extraction of the distances between the lesions was performed on the triangle wireframe. The wireframe view was very useful to perform a more accurate analysis of the area framed in Fig. 5*b*, which corresponds to the deepest abrasion. The zoomed view of this area is presented in Fig. 5*c*: here, the dimensions of the mesh triangles were smaller with respect to those in the neighborhood and show the variation in depth of the surface. The quantitative evaluation of the depression is well represented by the cross section of Fig. 5*d*. It is worth noting that the metric reticule overlapped to the 3D model in Fig. 5*e* allows the operator to precisely position the section and is of great help in the metrical analysis.

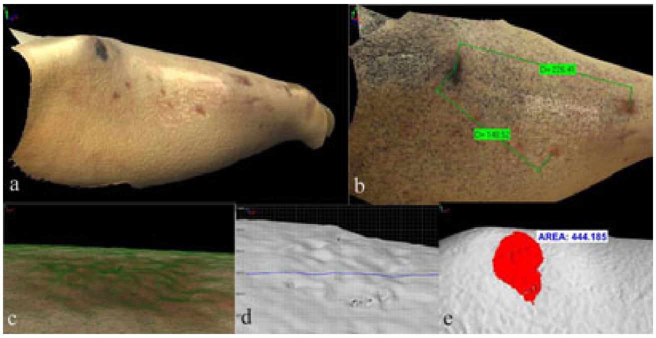

FIG. 5—*Case 1: example of application of the 3D optical digitizer. (a) 3D model of victim's skin surface; (b) measurement of the distances between the abrasions (wireframe representation); (c) wireframe view of the main abrasion framed in 5b; (d) cross sectioning of abrasion in (c); (e) area measurement of the framed abrasion.*

In the homicide case, the measurement on the victim's face was carried out by acquiring and merging three views at medium range. The resulting point cloud was used as the skeleton on which a proper number of smaller views at higher resolution (taken in correspondence with important details of lacerated and contused wounds) were added. In this way, a good trade-off between the quality of the mesh and the data was achieved. The 3D model is shown in Fig. 6*a* (only the depth information) and in Fig. 6*b* (depth information plus color). The aim was to study the sensitivity of the optical measurements, i.e., to assess if it was possible to gauge the shape, the depth, and the contour of the skin wounds on the frontal region of the head of the victim. Figure 7*a* shows the triangle mesh corresponding to the lesion framed in Fig. 6*a*. The model presents a high degree of adherence to the original shape and allows the extraction of the measurements, such as the depth of the wound and the point to point distances shown in Fig. 7*b*. The metallic rod underwent the same analysis, in order to carry out a comparison between the lesions and the blunt tool general characteristics. The chance to operate in a 3D virtual space allowed us to compare the pipe model, shown in Fig. 7*c*, with the lesion's morphological pattern. The two models were imported in the same workspace and were mutually oriented to verify the inclination and the direction of the blunt trauma. In Fig. 7*d*, the comparison and the virtual matching of the lesion and the tool supposed to have been used during the aggression are shown. The evaluation of pipe area which penetrated into the lesion may also allow one to get speed and strength of impact.

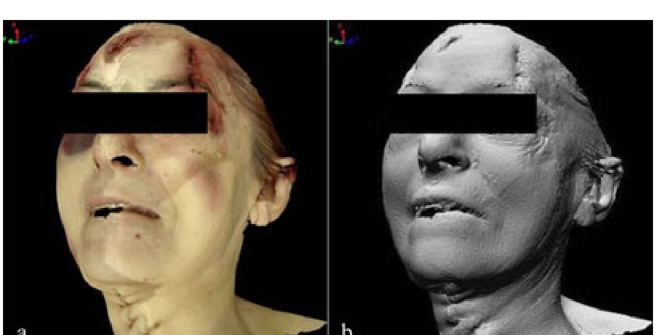

FIG. 6—*Case 2: 3D model of the victim's face. (a) Superimposition of the color information to the mesh; (b) rendered view of the mesh.*

In the third case, the analysis was aimed at acquiring the lesions produced by different sharp tools and at retrieving information useful for studying cut marks on bone. The optical digitizer was set up in the TELE mode, and previously tested on an uninjured femoral surface, in order to make it easier to recognize even the slightest sharp force lesions. To maximize the adherence of the measurements to the object shape, eight different point clouds were acquired and merged together. Then, the 3D mesh was created: this step was accomplished by using the Polyworks suite of programs (InnovMetric, Inc., Quebec City, ON, Canada). The resulting mesh is shown in Fig. 8*a*: the areas affected by the lesions are framed in blue. In the second area, the deepest four lesions were observed. Figure 8*b* shows a zoomed view of the mesh. This visualization is very helpful in performing quantitative observations of the surface. An example is shown in Fig. 8*c*: here, the lesion labeled "I" in Fig. 8*b* has been further zoomed; the wireframe representation of the model highlights the achieved degree of precision. In addition, in the figure, the results of two measurements extracted from the model are shown. Each one has been obtained by mouse-selecting a couple of triangles: their mutual distance is reported in the green frames (the measurement unit is millimeters). Following a similar procedure, a number of point to point distances as well as the selection of a section were assessed. Figure 8*d* shows the distances between the lesions (green lines), and the position of the section (blue line).

Discussion

This study has shown the application of 3D optical acquisition and 3D modeling methods to the gauging and analysis of lesions on soft tissues and bone from three forensic cases. Such technology reveals accuracy levels that make it suitable for quality control and measurement applications in the industrial production field. The experiment carried out in this project shows that it can be fruitfully used even to record, measure, and analyze with great accuracy the lesions produced on soft tissues, where the high degree of elasticity calls for a contactless approach to the measurement. The 3D analysis can produce information about direction, strength, and speed of trauma; it also gives indications concerning the tool which may have caused the lesion and is of help in the comparison between the lesion shape and the tool, with more precise indications than the pure morphological observation. As the instrument is compact, rugged, and portable, and the acquisition process is very fast, it can be used directly at the scene of crime. This is particularly important because the pathologist may only be able to accurately study the soft tissue lesions at the autopsy which may occur hours or days later with some inevitable change to soft tissue appearance. Moreover, it may be convenient to have a quick registration of lesions before the body is touched or removed or simply before a long time may go by before the autopsy is performed. It should be mentioned that with respect to classical toolmark analysis performed with casts as far as its application on bone is concerned, the 3D optical digitizing technology shows a slightly decreased performance in the case of bone lesions: the 3D models present a geometrical description of the edges which is less adherent to the real lesion profile, probably because of the actual limits concerning its resolution. Casts are easy to be assessed, while the 3D modeling process requires an adequate level of the operator skill, to quantitatively control the influence of the alignment and data editing steps, which are applied to the original data in order to obtain the 3D model. These aspects however are counterbalanced by the fact that the 3D model can be electronically sent over the internet and shared by the other operators involved in the investigation. Casting is more difficult and more frequently impossible on soft tissues.

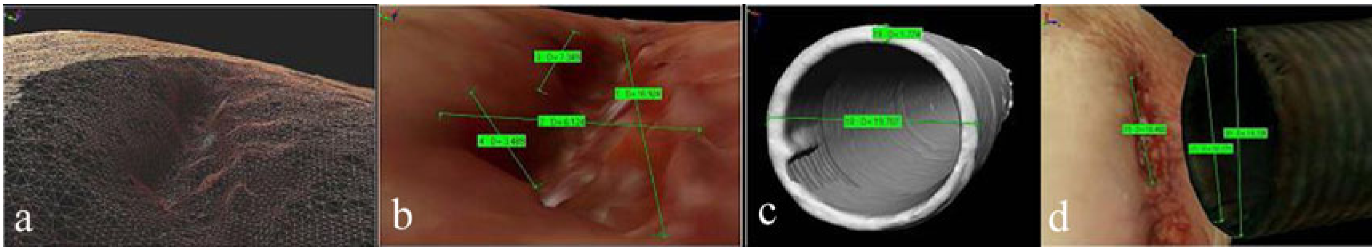

FIG. 7—*Case 2: application of 3D optical digitizer; (a) 3D model of the frontal lesion in Fig. 6a; (b) depth, width, and length measurements from the lesion in (a); (c) measurement of diameter and thickness from the 3D model of the metallic rod; (d) use of the 3D models to perform the metrical matching between the lesion and metallic pipe.*

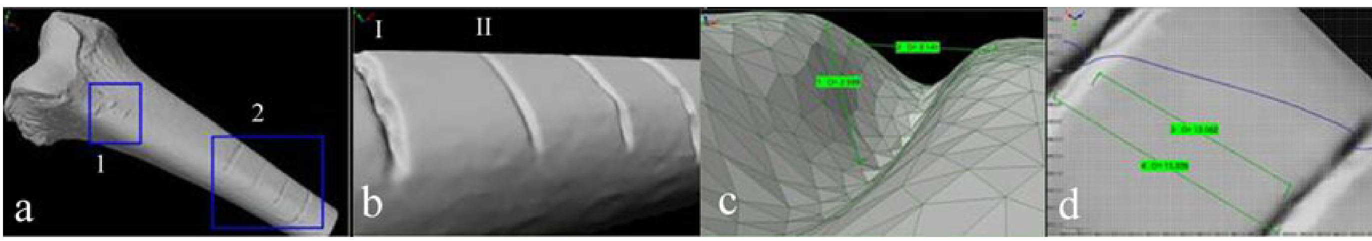

FIG. 8—*Case 3: application of the 3D optical digitizer to the femur; (a) 3D model of the femur, the analyzed areas are pointed out by blue frames; (b) zoom of the second area in (a); (c) zoom of the triangle model in correspondence with the lesion labeled by "I" in (b): extraction of the measurements; (d) example of the elaboration performed in correspondence with "I" and "II" lesions from (b).*

Thus, 3D optical digitizing technology brings a great improvement in the imaging study of lesions, particularly on soft tissues. It is worth noting that 3D optical sensors at higher performance are currently market available.

The use of a 3D optical digitizing system, far from being a sterile technological exercise, allows one to perform more precise measurements and produces a 3D model of a lesion, which can be stored for years, shared, and examined. More importantly, it allows one to immortalize a wound already from the scene of crime with consequent obvious advantages. Once again one should stress that 3D optics technology has a long and well-structured clinical background, but in forensics, literature on its use is not extensive (and therefore not proportional to the importance of this technology in capturing features which may soon be lost for the medical examiner) (23–29). Thus, the present study has not only enforced the scanty pre-existing literature but has also assessed for the first time application of this technology on saw marks in bone.

In conclusion, the application of 3D optical acquisition and modeling may have a crucial role for capturing and studying wounds on soft tissue as well as bone.

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Additional information and reprint requests:
Cristina Cattaneo, Ph.D., M.D.
Istituto di Medicina Legale
Università degli Studi di Milano
Via Mangiagalli 37
20133 Milano
Italy
E-mail: cristina.cattaneo@unimi.it