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Research Paper

The Application of DIC in Criminology Analysis Procedures to Measure Skin Deformation

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Abstract. In engineering, DIC is a widely used measurement technique. Its major advantage is that it provides real-time results (displacements, accelerations, stresses, strains, deformations) of the surface under examination relatively quickly and without contact. However, its application in medicine, biomechanics, and the field of criminalistics is novel. The present research focuses mainly on the frontier areas of forensics and medicine. The research aims to define the test boundary conditions and preparatory activities to measure the surface of the animal and then human skin. Injuries caused by low-energy ballistic bullets, blunt-force trauma, and cuts and punctures caused by knives and/or blades will be investigated. The present research focuses on puncture injuries in animal skin. The main challenge is to create a speckle pattern on the surface that can track deformation well. The research is about developing and validating this. The GOM ARAMIS measurement system was applied for the measurements. This paper demonstrates that a suitable preparation, painting procedure, and measurement setup has been established to measure the above effects, i.e., to identify displacements and deformations of up to tenths of a millimeter with sufficient accuracy. The evaluation of the results will also show that this method could be used in forensic applications, the automotive industry, medical orthopedics, and the textile industry.

Keywords: GOM ARAMIS; deformation analysis; knife wound; criminalistics; skin deformation measurement.

1. Introduction

The main objective of this paper is to develop a complete DIC (Digital Image Correlation) test method for measuring the injuries caused by punctures and low-energy weapons [1]. More specifically, the potential applications of DIC in fields other than engineering applications are investigated. The results will be useful in criminology, where they can be applied to the recognition and identification of physical evidence by applying them to forensic issues [2]. The application of tissue-engineered skin models and the advancement in flexible electronic skin for monitoring human physiological signals have shown significant promise in enhancing forensic analysis techniques [3]. Criminology can be considered as a sub-field of forensic science [4]. As defined by the California Association of Criminalists, forensic science is the profession and discipline that focuses on recognizing, identifying, individualizing, and evaluating physical evidence by applying the natural sciences to forensic science issues [5, 6]. Forensic science and legal medicine are closely related, focusing on forensic needs [7]. Regardless of the scope of practical medico-legal work, case reconstruction has always been a specificity in forensic medicine. This discipline is the opposite of pathology because it does not focus on diagnosing death and disease, but rather, legal remedies use the diagnosis as a starting point for reconstructing what happened [8]. The main aim is not to determine the cause of death but to clarify the circumstances and context relevant from a legal point of view [9]. The present research provides an opportunity to analyze from an entirely new perspective the extent of the injury caused by another person and its classification in legal terms, the analysis of injuries in terms of the object used to cause the injured person, and the recognition and interpretation of traces.

The tests were performed with the GOM ARAMIS 5M DIC system, which is of particular interest as this system is mainly used in automotive deformation analysis [10–13]. Several methods for measuring deformations and displacements are known from the literature and metrology practice. Conventional measurement methods include, among others, strain gauges and inductive

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displacement transducers. These methods require a lot of preparation and expensive tools and instruments. In contrast, the DIC methods presented in this research are non-contact methods that allow the investigation of the entire displacement and strain field on the parts of the specimen visible to the camera using common tools and post-processing. For these measurements, it is not necessary to know the location of the failure in advance since the measurement results are obtained for the whole specimen and are processed afterward. Digital image correlation as an inspection technique was first developed by a research group at the University of South Carolina in the 1980s and has been developed and widely used over the next three decades. Thanks to its many advantages, such as easy experimental set-up, variability, and widely adjustable time and spatial resolution, the DIC technique has become widely accepted as a helpful tool for measuring deformation. The main strength of DIC is that its principle is valid on microscopic (millimeter scale) and macroscopic (meter scale) scales. In addition to the meter range that can be used, it is interesting to note that the technology has not only been applied to test metallic materials but is nowadays also used for testing polymers, composites, and even biological materials. In addition to conventional test specimens, it is also used in complex components, machinery, or even building components, as well as in biomechanics and medicine, but its application in the forensic field is still novel [10–13]. It is worth mentioning that the laser scanner measurement solution is used in several engineering fields, either separately [14] or in combination with digital twin solutions [15].

The current article describes the applied surface preparation and special staining procedures. Also, it presents a 3D printed measuring frame developed in the laboratory, the main design criteria of quick specimen replacement and keeping the skin tissues in a stretched condition. The sub-modelled tissue was pigskin for the tests. The current research presents tests of five different stabbing tools commonly used in everyday life, along with the complete measurement process and validations. The evaluation of the results will also show that this method could be used in forensic applications, the automotive industry, medical orthopedics, and the textile industry.

The structure of the paper is as follows: Section 2 contains a literature review, Section 3 contains the materials and methods, Section 4 is about results and discussion, and Section 5 is the Conclusions.

2. Literature Review

In this section, the most critical literature is presented, which tries to support the actuality of the topic. It also analyzes the sources used to develop this study's instrument and research design.

2.1. Stabbing tools

One of the main tasks of this article is to assist criminological investigations using DIC technology, which is already widely used in the engineering world. Intentional homicide is one of the most serious crimes, and its investigation is not only prominent because of its seriousness but also serves as one of the best measurable and comparable indicators that can be used to track violent deaths and similar events. In 2017, the total number of victims of intentional homicide was estimated at 440,000 worldwide. Of these, roughly 1 in 5 were homicides in which the perpetrator inflicted a fatal injury with a sharp object [16–18]. Sharps injuries are the predominant form of homicide, most commonly caused by knives in the form of stab wounds, but many other sharp-tipped instruments can also be used as potential weapons and can cause serious injuries. Indeed, in a small proportion of cases, stabbings are committed with instruments that do not at first sight appear to be weapons, such as scissors, screwdrivers, corkscrews, forks, and needle rasps [16–18]. There are also tools familiar to the kitchen, such as various chef's knives, meat knives, bread knives, and spreading knives, as shown in Fig. 1. It should be stressed, however, that the study of stab wounds and the amount of technical and material resources devoted to them is far below the study of gunshot wounds. However, research on the ballistic limit of skin perforation, such as that involving BB-Gun pellets and cowhide simulants, provides valuable insights into the mechanics of injury and the effectiveness of various materials in replicating human skin properties [19]. In addition to investigating the mechanical properties of human skin and its simulants, recent studies have validated synthetic skin models such as the RBK 1518 synthetic chamois backed by 10% gelatin, which has shown to be a suitable simulant for non-deforming projectiles with specific sectional densities, thereby providing a consistent and reliable alternative for forensic and ballistic research [20]. Moreover, the mechanical properties of human skin and its simulants have been extensively reviewed, highlighting the challenges and advantages of using synthetic materials in forensic reconstruction studies [21]. As quantified in recent studies, the anisotropic behavior of porcine skin highlights the importance of considering directional variations in mechanical properties when using animal models for forensic investigations. Recent studies have validated synthetic skin models, such as the adjustable gelatine layer proposed by Hes et al. [22], which demonstrated the ability to cover the whole range of human skin v50% as reported in the literature, providing a consistent and reliable alternative for forensic and ballistic research.

It is now increasingly common for people to carry licensed firearms or legally permitted stabbing devices to keep themselves safe, so people may cause injury either in self-defense or intentionally, increasing the number of crimes that can occur [18, 23]. These offenses tend to hit the largest organ first, the human skin, as it is the first tissue covering the human body that will always be injured and from the damage to which the extent and nature of the injury can be determined [18, 23].

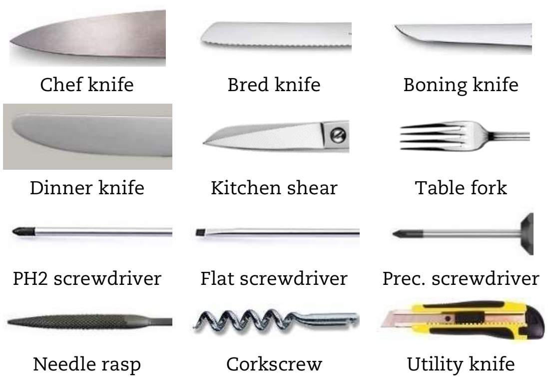

Fig. 1. Stabbing instruments (on the basis of [18]).

2.2. Properties and replacement of human tissue and fat layer

Identifying the appropriate material (i.e., specimens) to be tested is essential to conduct the research properly [24,25]. Human skin is often obtained during plastic surgery; common sources include the belly, breast, and back. These skin samples are stored in skin banks for scientific purposes. The same applies to human skin from deceased donors, which can also be used for research purposes. The demand for human skin for research is very high, but the supply is limited. As a consequence, alternative solutions need to be found [24, 25]. The anisotropic mechanical properties of human skin have been comprehensively characterized, showing significant dependence on both the orientation relative to Langer lines and the specific location on the body, as demonstrated by Ní Annaidh et al. [26].

The human skin is the largest organ in the human body, estimated to cover an area of nearly 1.7 square meters and make up about 10% of the average body mass [24, 25, 27]. The skin performs a wide range of essential functions in the body, one of its primary roles being to provide a protective barrier between the body and the external environment. The human skin is composed of four main layers: the stratum corneum, the viable epidermis, the dermis, and the subcutaneous tissues. Each of these layers has a specific and vital role in the skin's functions, and they work together to help maintain skin health and function.

The anisotropy of human skin, a critical consideration in biomedical research, reveals that skin's mechanical properties vary significantly with orientation and location, particularly relative to the Langer lines, which are natural lines of tension [26]. This variability is highlighted by Lakhani et al. [28], who demonstrated the directional dependence of mechanical properties in porcine skin, showing significant differences in modulus and collagen fiber orientation across different directions. A study examining tensile properties of human skin from different orientations on the back found that the ultimate tensile strength, elastic modulus, and strain energy are significantly influenced by these orientations, confirming the skin's anisotropic nature. Histological analysis corroborated a strong correlation between collagen fiber orientation and the Langer lines, further elucidating the structural basis for this anisotropy. This data is crucial for modeling skin behavior accurately, aiding in various fields such as surgery and impact biomechanics [26].

Over the past decade, medical research has increasingly focused on finding and developing alternative skins from non-human sources, such as primates, pigs, dogs, cats, rodents, rabbits, and fish. Research has shown that pig skin shows remarkable similarities to human skin in overall structure, thickness, hair follicle content, pigmentation, collagen, and lipid composition. The pig is considered an excellent surrogate model in many areas of biomedical research because of its similarity to human skin. The similarities in anatomy, physiology, and the immune system allow pigs to be used effectively in a variety of research and experiments and to apply their results to humans. The hypodermal tissue and its relationship to the skin are key to the similarities and allow the use of pig skin in human skin research and studies. In pigs, the thickness of the stratum corneum has been shown to be approximately 20-26 μm, which is comparable to that observed with human skin. The thickness of the epidermis, the upper layer of skin, in pigs varies between 30 and 140 μm, whereas in human skin, it ranges between 50 and 120 μm. Moreover, considering the skin-to-epidermis thickness ratio of 10:1 to 13:1, the similarity between pigs and humans is again evident. It is important to note that, in general, the sub-dermal fat layer is thicker in pigs than in humans [24, 25, 27].

Another challenging task in forensic and criminological practice is the determination of the force used during stabbings or the estimation of the minimum force required to penetrate the body (i.e., break the skin) with a given weapon or sharp tool. Literature [29, 30] suggests that ballistic gel ensures adequate resistance is felt during knife penetration. Ballistic gel is one of the best substitutes for the fat layer. Using gelatin blocks can result in similar penetration depth and permanent damage as observed in soft tissues. In modern wound ballistics studies, gelatin blocks of 10% or 20% by weight are used, conditioned to 4 or 10 °C. Both percentages give good results, but in most studies, the 10 percent by weight is used. The 10 wt% gelatin blocks conditioned to 4 °C have resulted in a penetration depth of within 3% of that seen in live pig leg muscle in various studies. For the same percentage by weight, a 4.8 mm diameter bullet projectile in gelatin and the legs of anesthetized pigs followed a similar trajectory in both targets and showed a penetration depth within 1%. The 20 wt% gelatin varies in that it is conditioned at 10 °C. This type is much stiffer than the 10 wt% gelatin and has a shorter penetration depth. Various studies have also investigated the aging process of ballistic gelatine. In these studies, a gelatine block was observed and tested for 5 days, and the penetration depth was measured continuously. Under refrigerated storage conditions, the ballistic gelatine did not change its lifetime, and no aging was detected [29, 30].

2.3. Examination of skin tissue deformation

Following the literature review of skin tissues, the paints and painting methods applied to skin tissues will be analyzed. It was important to consider methods that can be applied to animal skin and living human skin.

Creating a suitable pattern and a gloss-free surface is essential for DIC measurement. The most common way to achieve this is to spray or airbrush the skin surface. Water-based paints are preferred because of their skin-friendly properties. A new solution for preparing samples, especially live samples, is using temporary tattoos, which can be laser or inkjet-printed tattoo papers [31, 32]. The steps to produce a "tattooed" speckle pattern are the creation of a random patch pattern and its printing on paper. Then, the finished tattoo paper must be adjusted to the size of the test specimen. After removing the layer protecting the pattern, a sticky surface is formed, which allows the pattern to be applied to the surface of the pre-cleaned specimen. A damp cloth is used to soak the base layer, and the diffusion of the water causes the pattern to dissolve from the base layer and become visible on the surface of the specimen [31, 32].

Many articles deal with the determination of the mechanical properties of skin. Kalra et al. [33] provide a comprehensive overview of the mechanical properties of human skin. The primary objective is to measure the Young's Modulus of the skin, a crucial parameter for understanding skin characteristics, disease progression, and the effectiveness of cosmetic applications. The study employs various mechanical testing methods, including tensile, indentation, suction, and torsion tests. Results indicate that the Young's Modulus of human skin ranges from 5 kPa to 140 MPa, highlighting the skin's highly anisotropic and viscoelastic nature. Different testing methods yield varying results, with suction tests being particularly favored for in vivo applications due to their ease of use and ability to account for both in-plane and normal loading conditions. The paper emphasizes the importance of selecting appropriate testing techniques for clinical and cosmetic evaluations, providing valuable insights for medical, dermatological, and cosmetic fields.

The article written by Maiti et al. [34] explores how natural stretching affects skin mechanics. The study uses Optical Coherence Tomography (OCT) and Digital Image Correlation (DIC) to measure changes in skin surface strain and sub-surface deformation on the volar forearm during arm movement. By changing the arm angle from 90° flexion to 180° full extension, the researchers observed a 25% increase in skin surface strain. Epidermal thickness decreased by 20%, and significant reductions in skin surface roughness and flattening of the dermal-epidermal junction (DEJ) were noted. The study highlights the efficacy of combining DIC and OCT as a non-invasive, real-time methodology for analyzing structural changes in the skin. This approach can significantly impact the design of exoskeletons, prosthetics, orthotics, and wearable sensors, enhancing their comfort and effectiveness. The findings emphasize the importance of understanding skin mechanics for various medical and consumer applications.

Palanca et al. [35] provide an overview of digital image correlation (DIC) to measure displacements and strains in biomechanical applications. It covers DIC's principles, its use from microscopic to macroscopic scales, and its strengths and limitations. The review emphasizes the importance of accurate surface preparation with high-contrast random speckle patterns for precise measurements. DIC's non-contact nature and full-field measurement capabilities make it ideal for studying both hard and soft tissues under various mechanical loads. The technique's effectiveness is demonstrated by studying strain distributions in human tendons, cartilage, and bones. DIC's integration with finite element analysis (FEA) enhances experimental outcomes. The paper concludes that DIC is a versatile and powerful tool in biomechanics, offering detailed insights into tissue mechanics essential for both research and clinical applications.

Liu et al. [36] explore the use of Optical Coherence Tomography (OCT) and Digital Image Correlation (DIC) to measure finger-pad skin deformation. This study addresses the lack of research on sub-surface layer deformation during sliding. The researchers used OCT and DIC to examine a 25-year-old female's finger-pad under normal and shear loading. They observed a reduction in contact ridges and deformation at the stratum corneum junction during sliding. DIC analysis showed higher surface strain near the distal interphalangeal joint compared to the fingertip. This novel approach provides a non-invasive method to study structural changes in finger-pad skin, with potential applications in medicine, bioengineering, and consumer products. The findings highlight the different behaviors of finger-pad regions during static and dynamic phases, contributing to a better understanding of finger-pad friction mechanisms.

As the literature shows, DIC technology is used to measure skin deformation but is not yet widely used to measure its mechanical properties, more so for analyzing criminological problems, i.e., puncture wounds. In the present research, the novelty is adapting a DIC technology to a high-precision deformation testing system developed for the mechanical field, which has not been used for this task. The paper's main focus was to investigate the applicability of the DIC system and develop the measurement process.

3. Materials and Methods

This section describes the materials, puncturing/cutting tools, and penetrators used in the experiments. It also describes the materials used for cleaning the skin and the paints and measuring devices used for the test. The measuring frame developed for the test using 3D printing technology will also be presented.

3.1. Materials and equipment

This sub-section describes the materials and tools used in the experiments.

3.1.1. Skin

The present study uses skin from the abdomen (belly) of the pig. Before the tests, the skin was stored refrigerated on a damp paper towel to preserve its elasticity. For the study, 90×90 mm samples were cut from the hypodermis-cleaned skin, taking care to avoid any mammary or skin defects. The specimen was then identified with a cover sheet.

3.1.2. Ballistic gel

In this article, the ballistic gel was placed in a measuring frame specially designed and manufactured for the present research. Based on the literature data, a mixing ratio of 10% was used. Gel powder and water were mixed in a lump-free 10-90% ratio. It was then placed in a refrigerator at 5-8°C for 24 hours. It was put into the frame at the time of use, just before the measurements.

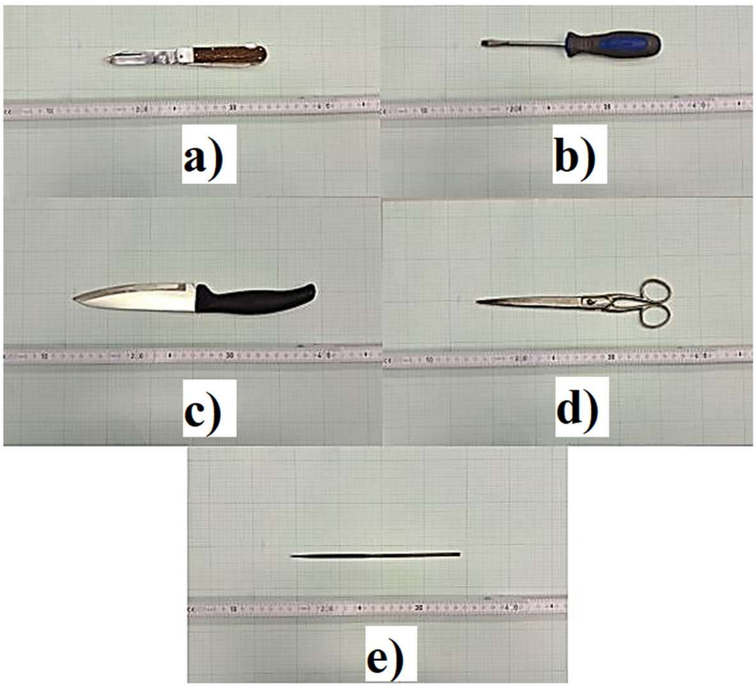

Fig. 2. Stabbing tools (a) knife; (b) flat screwdriver; (c) kitchen knife; (d) scissors; (e) needle rasp.

Table 1. Paints.

ID	Name	Producer	Brightness	Color	Base (min 40%)
P1	Acrylic Primer	Maestro	mat	RAL9003	Acetone
P2	Chalk Finish Mint Green	Pinty Plus	mat	CK794	Acetone+Water
P3	Acrylic	Prisma Color	silky	RAL9005M	Acetone+ethyl acetate
P4	Acrylic	Pinty Plus Evolution	mat	RAL9005	Water+Acetone

Table 2. Surface cleaners.

ID	Name	Brand	Producer
SC1	warm water	-	-
SC2	liquid soap	Bale Milde Seife	DM
SC3	dishwashing liquid	Pur Balsam Calendula	Henkel
SC4	alcohol hand sanitizer	Brado Life	Brado

3.1.3. Stabbing and cutting tools

Five different stabbing tools were selected for the tests, considering the literature and the Hungarian legislation (a blade length of more than 8 cm is considered a weapon [37]). The main criterion for the selection was the use of tools that are common in everyday life and found almost everywhere. This is important because these instruments are easily accessible to anyone, are not subject to licensing, and are often at the center of violent crime as weapons. The devices chosen have different geometries, and these designs can have different effects on skin tissue, which is a crucial aspect of this research (Fig. 2).

3.1.4. Paints

When using DIC, the literature and the experience of the authors of the current paper suggest that the following properties of paints should be taken into account [38]:

- matt gloss - no reflections during measurement,
- flexible - must follow the deformation of the specimen,
- deep black color - contains good quality dye,
- water-based - more suitable for indoor applications,
- easy to spray - preferably not diluted, as this will degrade the spectrum,
- cure permanently after more than 24 hours to maintain elasticity.

These are often contradictory criteria, which make it challenging to find the right color for the proper application, and the composition of colors can vary from one country to another due to different specifications. Considering all criteria, the following paints were selected for the research (Table 1).

The paints are easily accessible and available in white and black for primer coats and speckle patterning. It is important to note that the paints will be used to transfer (transmit) the deformation of the skin tissue toward the cameras, so their role is crucial. This has been demonstrated in previous research by the authors of the current article on metallic and polymeric base materials.

3.1.5. Surface cleaners

Preparation of the skin surface before the painting process is of high importance. This is common on industrial parts, but the skin's surface is different, so different methods have to be used. The pre-skin surface is covered with a natural layer of fat. This layer makes it difficult for the paint to adhere, so it must be removed. When choosing cleaning products, it is crucial to avoid damaging the skin's surface and structure; therefore, using corrosive, aggressive products is not allowed. Taking these considerations into account, four different cleaning agents were used, which are acceptable on human skin (Table 2).

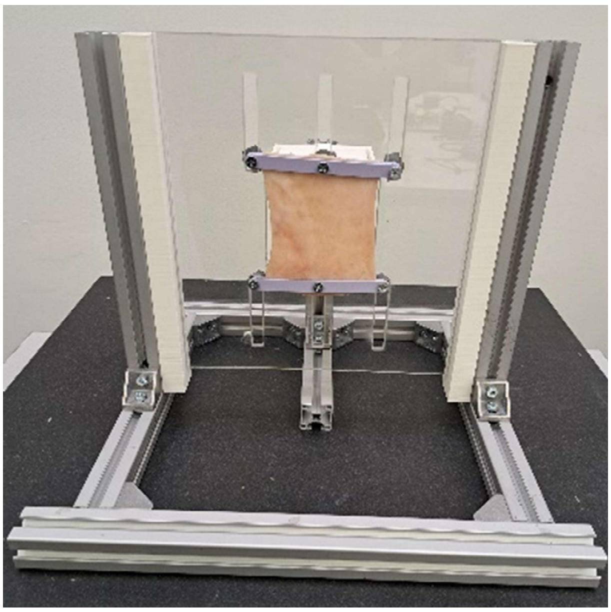

Fig. 3. 3D printed fixture (frame).

3.1.6. 3D printed measuring fixture (frame)

The skin specimen must be adequately stretched or placed in front of the ballistic gel to perform the measurements properly. To do this, it was essential to prepare a measuring frame (see Fig. 3). In addition to cost-effectiveness and simplicity, the frame was designed to allow rapid specimen exchange.

The frame elements (grey) are made of ITEM aluminum profile 30×30 mm. The mounting, clamping, and other elements (purple) are 3D printed PLA. The ballistic gel holder and the mounting plate (white) were made of 1.75 mm thick Plexiglas for better visibility (Fig. 3). The production of the skin gripper was particularly challenging. The fastener is one of the key elements; it was important to design notches to ensure that the skin would not slip out and hold it tightly in the frame, allowing it to be adequately stretched. The geometry of the notches of the gripper is a truncated pyramidal shape with the following dimensions: 1 mm height, 1.2 mm width, and an angle of 66 degrees. The notch of the gripper is in full-length contact with the skin, ensuring a uniform geometric contact at all points of the skin.

3.1.7. GOM ARAMIS

The GOM ARAMIS 5M measuring system was applied for the tests in the research. ARAMIS systems perform non-contact and material-independent measurements based on the principle of DIC. These systems offer a reliable solution for full surface and point-based inspections from a few millimeters to several meters. The ARAMIS range of sensors can dynamically measure 3D coordinates, 3D displacements, and 3D surface deformations. In addition, material characteristics can be determined, including FLC (Forming Limit Charts) and tensile tests using the DIC technique. The latest technology now uses two 12-megapixel cameras providing high local resolution. Not only small deformations but also local effects in large areas can be measured. The interchangeable camera bracket and pre-adjusted, manufacturer-certified measuring lenses make the job easier, allowing the system to be quickly and easily modified to suit the needs of the area to be measured. Designed for industrial use, the systems are stable, so sensor calibration is less often required. The maximum image capture rate of the ARAMIS 5M is 25 fps at full resolution, and this can be increased by reducing the width or height of the image so that any component malfunction can be documented in detail promptly. [10, 39]

The measurement task is to compare a series of images of a speckle-patterned specimen, finding and tracking identical points across the entire series of images. Searching for individual pixels between two images is not always successful since the color and/or intensity value of a pixel may be the same as that of several pixels in the reference image. To solve this problem, a small area (facet, sub-frame - hereafter referred to as the evaluation window) is selected in the vicinity of a pixel and identified between images. The evaluation window is usually square and can be clearly identified on the whole image sequence due to the sample's unique pattern during the test specimen's preparation. There are several methods for finding the area around a pixel in another image, the two most common being normalized cross-correlation and normalized least squares. In order to achieve sufficient accuracy, the deformation of the evaluation windows must be taken into account, for which some form of iteration is usually used. Most DIC software uses some variation of the Levenberg-Marquardt algorithm for nonlinear optimization. [10, 40]

Using the correct pattern in DIC tests is essential to reduce measurement noise and improve the accuracy of measurement results. GOM systems include a reference image for the ideal speckle pattern. When preparing the specimens, care should be taken to ensure that the painted pattern is as similar as possible to the pattern required for the range of measurements. A suitable quality pattern is necessary because during DIC, a small area of the image, the evaluation window, is monitored as the sample is deformed and compared with the reference image. The aim is to get the best possible fit of the evaluation window until the end of the measurement. This is calculated by continuously monitoring the variation of the grayscale and the match between the images. As described above and based on previous preliminary experiments, test specimens with appropriate patterns were used for the measurements. [41]

3.2. Methods

This subsection describes the measurement procedures and processes used in the process.

3.2.1. Preparation of specimens

90×90 mm specimens were cut from the pigskin used for the study. The inner fat layer of the skin was removed with a medical scalpel. Subsequently, the specimens were cleaned using the cleaning agents previously described. A reference skin was also used for the tests, which did not undergo this cleaning. The cleaning process was as follows:

- skin slight stretching,
- application of a small amount (10 ml) of the appropriate identification cleaner to the surface,
- mechanical abrasion,
- rinsing with mild-temperature water,
- drying of the surface,
- storage in a refrigerator on a damp cloth until use (max 24 hours).

3.2.2. Tests of paint(ing)s

The first step was to apply an even coat of primer. This is not yet a speckle pattern, but it is a very important step, as the layer of paint will transmit the skin's deformation. Traditional paint layer testing methods are limited here.

Touch test

The test procedure is a subjective measurement method. Its purpose is to determine the time after which the test specimens are movable, i.e., they no longer leave a trace to the touch. This is necessary because, during the preparation of the specimens for a DIC test, it is often the case that the specimens have to be dried in a place different from where the paint is applied. This test can determine the shortest time the paint has dried to the point where it does not leave a stain (spot) but still stains with a small amount of force. Other tests cannot be started within this time.

For the test, the test specimens shall be inspected every 5 minutes after painting, where the painted surface shall be touched by hand and checked for traces of paint. The use of rubber gloves is mandatory for the test. If the paint leaves a mark, the test shall be repeated after 5 minutes. If there is no stain, the test sample has passed the test. [11]

Print-Free test

During the test, the touch drying of the paint is determined. Compared to the previous test, this test shows how much time has elapsed since the paint can be loaded, i.e., the paint is not yet solid but does not stain or peel off the surface when weight is applied. The test is based on ISO 9117-6:2013 - Paints and varnishes. Drying tests - Part 6: Print-free test and ISO 9117-5:2013 - Paints and varnishes. Drying tests. Part 5: Modified Bandow. Wolff test. Applying these two standards is justified because DIC tests should not be performed on paints that have dried in the wet state, based on literature data and practical experience. After all, if the paint is no longer elastic, it cannot transmit the deformation. Some deviation from the two relevant standards is therefore necessary. The modification concerns only the weights applied, the maximum load of 1000 g. At this weight, the paint is already sufficiently solid and stable; it does not separate when the pieces are moved or clamped (gripped) but has the expected elasticity, i.e., it has not yet hardened. [42,43]

During the test, a 26 mm diameter circular paper (80 g/m2) is placed on the painted surface, followed by a 22 mm diameter 5mm thick rubber element (hardness 50 IRHD +- 3IRHD, ISO7619). Weights are placed on this rubber element, with a load of 20 g, 200 g, 500 g, and 1000 g in weight units. Each weight shall be loaded on the surface for 60 seconds, after which the test piece shall be tapped on a 30 mm thick wooden surface from a height of at least 20 mm. If the paper falls off, the following weight is applied. If it sticks to the paint, the test shall be repeated after 15 minutes. A given paint passes the test if it passes the 1000 g load. The test determines the time after which the test specimen can be loaded. The test shows the load capacity but does not show whether the paint adheres well to the surface to be tested, so further testing is required. [42,43]

3.2.3. Speckle pattern

These tests were followed by the application of speckle patterns. Two different methods were used in the research: the manual spray application of paint and the airbrush spraying method, which is in accordance with the literature.

- Spray

  The speckle pattern was applied using a sub-coat of the paints described earlier in a well-ventilated area, with the plume held at the correct dead-center position, the so-called spit boundary. The advantage is that it does not require any special equipment and is accessible to anyone, but the disadvantage is that it requires experience and a lot of practice.

- AirBrush

  The paints shown can also be applied with an airbrush. Airbrush systems use a fine spray technique that atomizes the paint using compressed air. This allows for precise and detailed painting, often used in artistic, industrial, and cosmetic applications. The airbrush technique is particularly popular in modeling, car painting, and make-up art. The systems have different nozzles and compressors that allow precise control of the paint flow and spray pattern. After tapping the spray bottles at 2.5 bar pressure and adjusting the spray pattern to the correct sprayed pattern, the speckle patterns were applied.

3.2.4. DIC measurements

Using the previously presented GOM ARAMIS 5M DIC measuring system, measurements were taken after painting. For all specimens, measurements were completed between 3 and 12 hours after painting. For the measurements, the CP90 measuring range was used; the test distance was 836 mm, which corresponds to the standard measuring distance of the machine at this measuring range. A sampling frequency of 25 Hz was used for the tests, with a full-resolution setting. The ballistic gel cube was replaced before each measurement per specimen. The test parameters are, therefore, as follows:

- Caliber Panel: CP90,
- Measuring area: 110×120 mm,
- Camera distance from the 3D printed frame: 836 mm,
- Resolution: full resolution,
- Measuring frames: 25 Hz,
- Camera slider distance: 316,
- Camera angle: 25°.

All the stabbing tools were used by the same person taking the measurements, with a starting distance of 50 cm. The force is, of course, not controllable due to the human staff, but the puncture force, speed, and point of attack (point of penetration into the test specimen) were practiced before the tests. This method was agreed with the police and the National Defence University and is a common and accepted method in forensic reconstruction studies. The measurement setup is shown in Fig. 4.

Fig. 4. Measuring setup.

3.2.5. Evaluation methodology

The evaluation methodology used is mainly based on a graphical (and visual), as well as mathematical-statistical analysis of the 3D-DIC measurements performed. The article's novelty lies mainly in the forensic application of the DIC measurement technique, in this case, including (animal) skin. In the future, the authors also plan to apply an evaluation technique that could help the subjective assessment of stabbing wounds. This includes using fuzzy methods, which allow considering intermediate categories in a multi-criteria analysis. Examples of such literature include [44-46]. Exciting measuring methods can be computed tomography [47] and/or wave propagation [48] combined with finite element method [49-51].

4. Results and Discussion

This section presents the results of the tests, the descriptions of which are given in Section 3. The results are divided into two main groups: painting tests and deformation tests. In the first group, the results of the cleaning and painting tests are presented, while in the second group, the applicability of the DIC system and the deformation and penetration of the filtering tools on the skin tissue are described.

4.1. Results of painting tests

The first of the tests to be completed was the cleaning test. The specimens were prepared using all four cleaning methods and sprayed with all four paints; this, in combination with the reference specimen, gave a 5×4 test matrix. Following the painting, a touch test was completed, followed by a print-free test. The results are summarized in Tables 3 and 4. Figure 5 shows a specimen's part of the tests.

Table 3 shows the drying results of the touch test. It can be clearly seen that the paint cannot even dry appropriately on the reference specimen because the greasy surface has dissolved the paint.

Table 4 shows the results of print-free tests. It can be seen that the paint was fully covered, but the adhesion between the layers was not achieved. This is very important, as the paint transmits the deformation of the skin to the cameras, so the measurement result can only be as good as the contact between the surfaces. Studying the events, it can be seen that P2 and P4 specimens were the quickest to achieve print-free drying and also behaved best in the cleaning tests.

4.2. Results of Deformation Tests

Taking into account the results of the preparatory tests presented in Section 4.1, the deformation tests were carried out only with P2 and P4 paints, using a detergent cleaning procedure. The images of the measurement results will show the axial displacements in the Z direction, i.e., in the same direction as the direction of the puncture. Stress values are not presented due to a lack of force measurements, but this was not the task of the present research. The following evaluation aspects were considered for the measurement results:

- maximum deformation at the moment of puncture (mm), this indicates how much deformation, i.e., damage, the puncture tool causes,
- the residual deformation after puncture (mm), which also indicates the degree of damage,
- the behavior of the paint around the cemented hole, whether so-called blind spots are formed,
- breakthrough time, how quickly the stabbing tool can penetrate the material,
- penetration depth in mm indicates the depth of penetration into the ballistic gel.

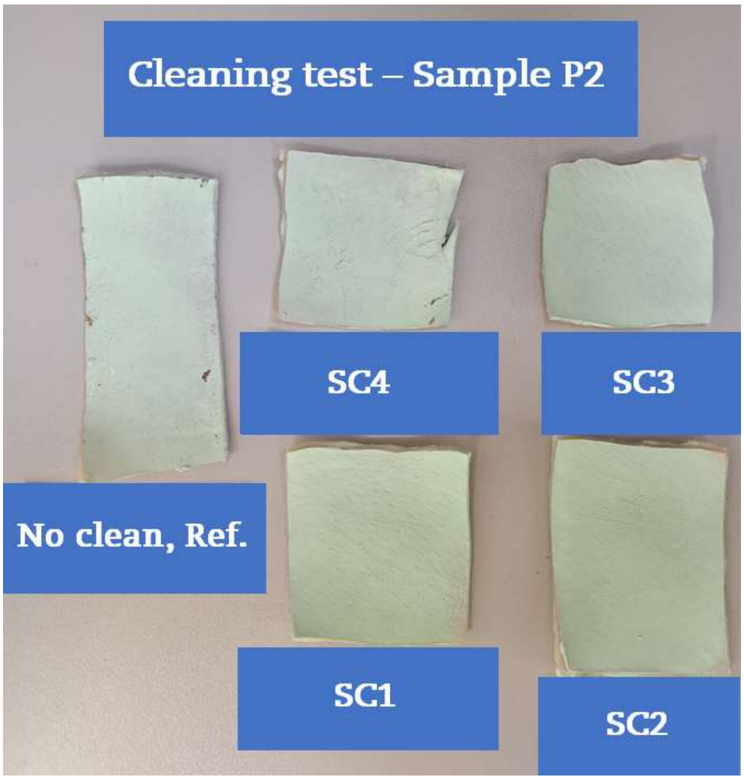

Fig. 5. Cleaning and painting test with the P2 paint specimen before the print-free test.

Table 3. The measured drying time values (OK means adequate, NOK means inadequate).

Paint types	Surface cleaner types	Drying time [min]								
		5	10	15	20	25	30	35	40	45
P1	Reference									NOK
P2										OK
P3										NOK
P4										OK
P1	SC1						OK			
P2						OK				
P3							OK			
P4							OK			
P1	SC2							OK		
P2						OK				
P3						OK				
P4						OK				
P1	SC3						OK			
P2								OK		
P3								OK		
P4							OK			
P1	SC4				OK					
P2					OK					
P3						OK				
P4					OK					

Table 4. Print-free drying time values.

Paint types	Surface cleaner types	Print-free drying time [min]
P1	Reference	failed
P2		200
P3		failed
P4		failed
P1	SC1	120
P2		50
P3		55
P4		45
P1	SC2	35
P2		25
P3		25
P4		25
P1	SC3	30
P2		25
P3		25
P4		20
P1	SC4	40
P2		35
P3		45
P4		30

Figure 6 shows a state during measurement. The captured painted specimen and the puncture tool are clearly visible. The figure on the right also shows the deformation of the ballistic gel. For the interpretation of the plots, it is important to note that the values of the color spectra differ. This was necessary because there was a large variation between the results of the different stabbing tools, and if the minimum and maximum displacement values were used, the small details would not be visible. Each result shows the displacement in the Z direction in mm. Figure 7 shows the results of the kitchen knife measurements.

Figure 8 shows the needle rasp punching. It can be seen that it gives a similar result to the kitchen knife, but because the opening is smaller, the total surface damage is less, i.e., it can be used with much less resistance.

Figure 9 shows images of punctures made with household scissors. The differences are clearly evident. It causes much more deformation before the breakthrough, i.e., it is much harder to penetrate the skin and is likely to cause more pain. It also has a much greater residual deformation of 1.5-2×, i.e., much greater damage.

Table 5 illustrates the depth of puncture in ballistic gel. From the results of the DIC and depth measurements, it is clear that the needle puncture can cause the deepest wound with the least resistance.

Table 5. Depth of the puncture (the ID of the stabbing tool can be found in Fig. 2).

Stabbing tool	Depth of puncture [mm]
(a)	85
(b)	65
(c)	110
(d)	85
(e)	100

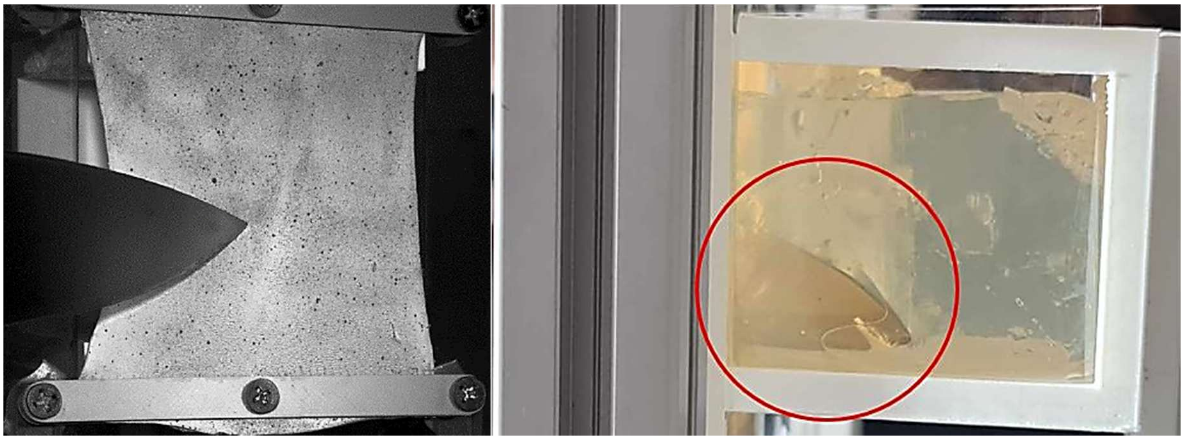

Fig. 6. A moment during measurement and an example of a stabbing tool penetration.

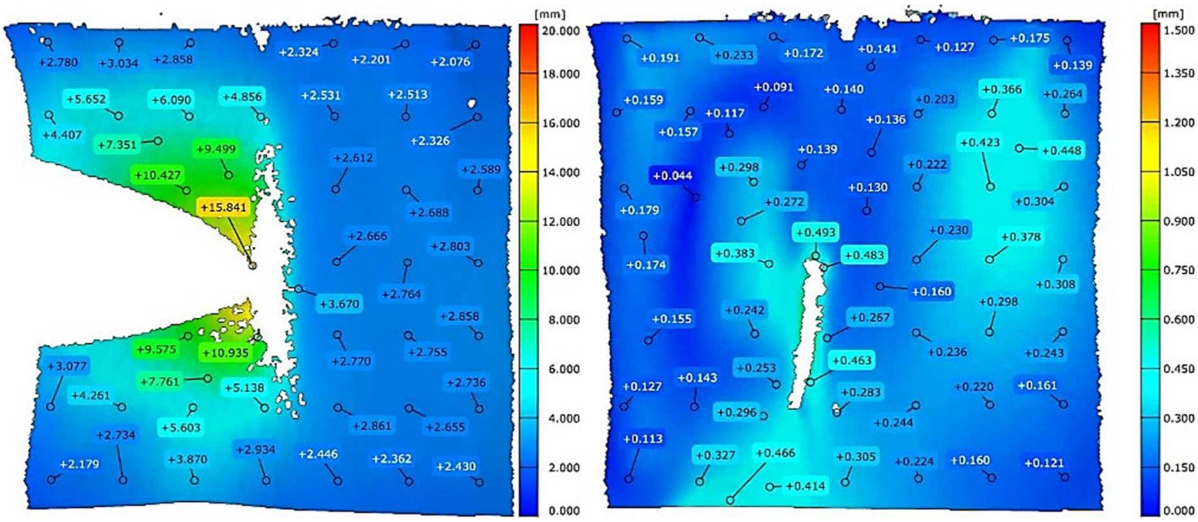

Fig. 7. Pictures of a knife puncture, on the left the moment before the tear, on the right the moment of rest after the pull-out.

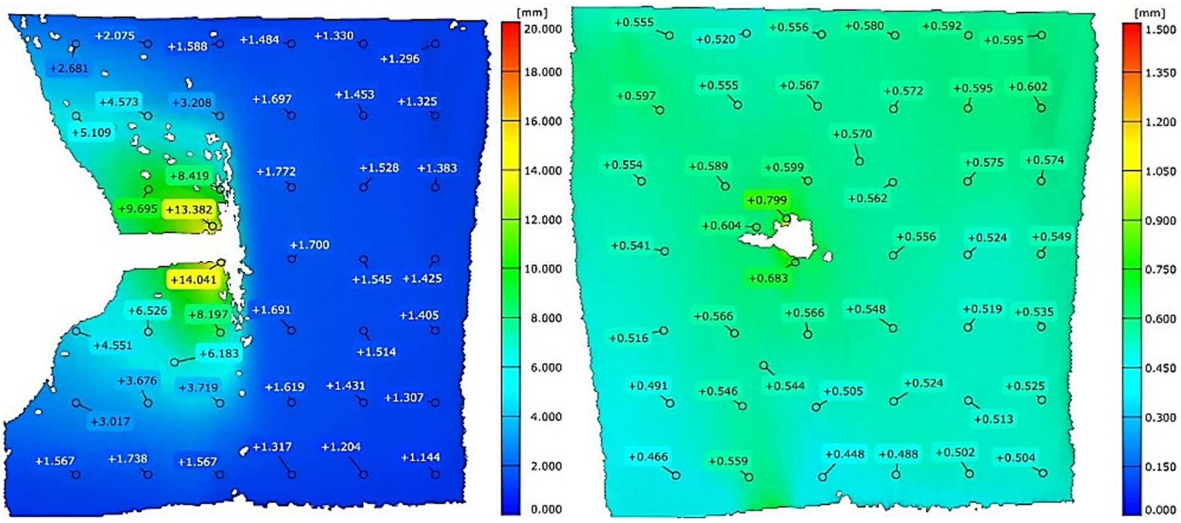

Fig. 8. Pictures of a needle rasp puncture, on the left the moment before the tear, on the right the moment of rest after the pull-out.

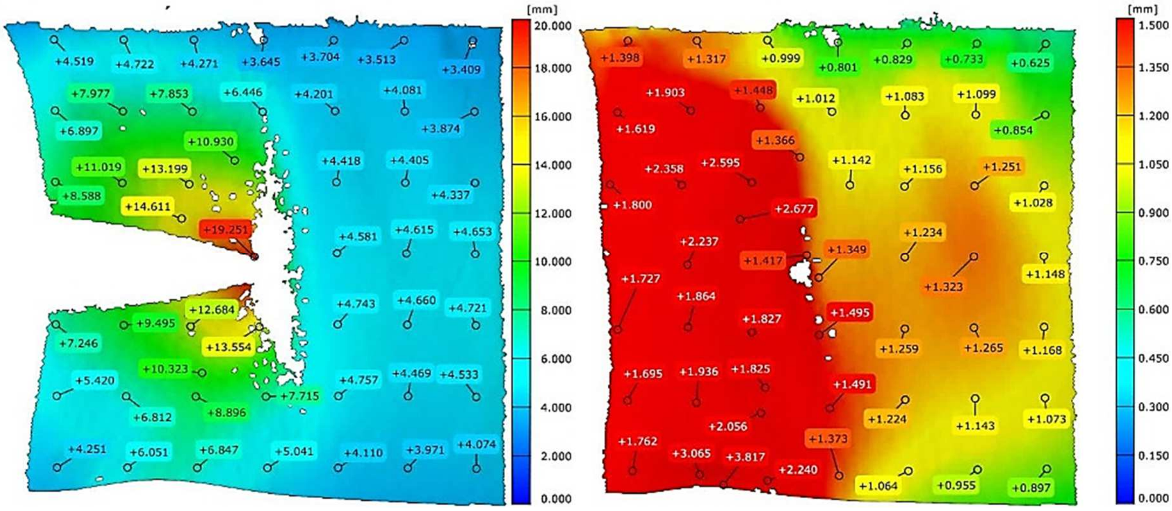

Fig. 9. Pictures of a puncture by scissors, on the left the moment before the tear, on the right the moment of rest after the pull-out.

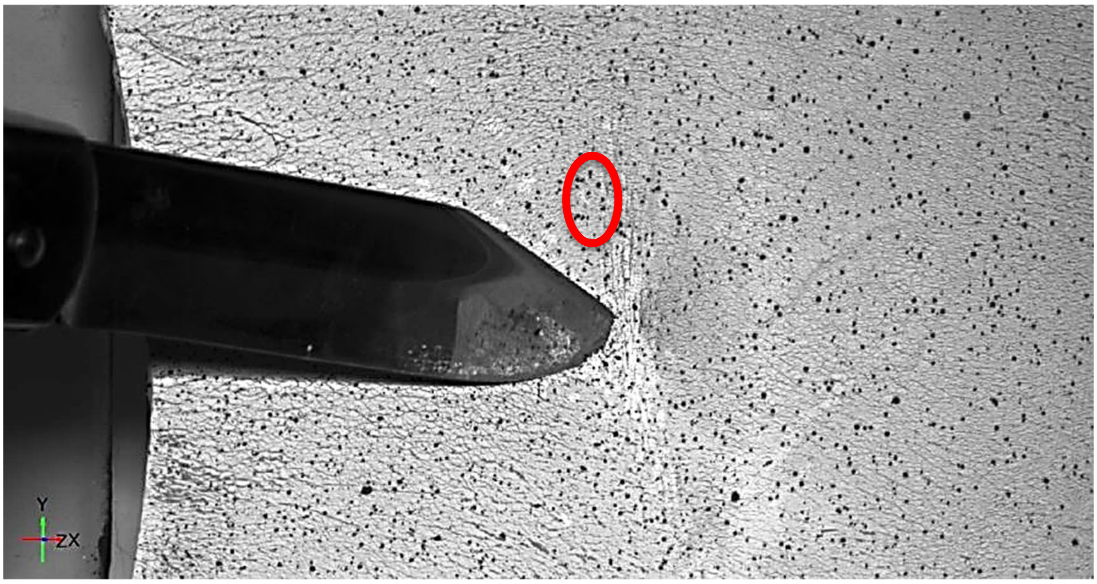

Fig. 10. The "blind spot" in the measurement.

Concerning paints, the blind spot studies have shown similar results. The deformation of the skin tissue near the opening was so significant that the dyes had separated from the surface and could not show any results in the immediate vicinity of the opening. This is also shown in Fig. 10. This also occurs in engineering applications, but deformation of this magnitude is not normally encountered there, so the effect is less pronounced. Further research will have to reduce the extent of this further, but the results obtained are as expected and can be used for criminological purposes.

5. Conclusions

This research successfully demonstrated the application of Digital Image Correlation (DIC) techniques in forensic analysis for skin deformation, providing precise measurements of surface displacements and deformations down to tenths of a millimeter. These insights reveal the mechanics of puncture wounds and blunt force trauma, extending the utility of DIC beyond traditional engineering applications into criminology and forensic sciences. The ability to accurately measure skin deformation from various weapons equips forensic experts with a novel tool to analyze injury mechanisms, which is crucial for establishing the precise force of impact or the nature of the weapon used in legal proceedings.

The methodologies developed also show promise for broader applications in the automotive industry, medical orthopedics, and the textile industry, where they can enhance understanding of biomechanical effects and inform the design of safer vehicles and more effective medical implants. However, the study faced limitations, including the use of animal skin models, which do not perfectly replicate human skin behavior. Future research is directed to include human skin tests and explore the response of different biological tissues to various trauma types, enhancing the versatility of DIC techniques.

Significant results were observed in both the painting and deformation tests. Surface preparation tests demonstrated that household soaps, dishwashing detergents, and hand sanitizers are effective for cleaning skin surfaces, while refrigerated storage on damp wipes preserves skin elasticity. The water-based matt paint (P4) and chalk paint (P2) performed best, although "blind spots" were observed in deformation tests. These paints, while not yet suitable for "live" specimens due to skin irritation, are effective in other contexts. The ARAMIS 5M DIC system showed that it could be applied effectively in this area, with certain stabbing tools identified as more destructive or able to penetrate with less resistance, providing a new perspective and methodology for criminological research.

Collaboration among forensic scientists, biomechanical engineers, and material scientists is essential to refine DIC methods and explore new applications, promising breakthroughs in forensic science, and other fields requiring detailed deformation analysis. Enhanced forensic techniques through advanced DIC methods contribute to more accurate crime scene reconstructions and fairer legal outcomes, supporting the judicial system in making informed decisions and impacting societal trust in legal and scientific institutions. This study lays the groundwork for future explorations and sets a precedent for integrating sophisticated imaging technologies in legal medicine and beyond, with ongoing potential to impact various industrial and research fields.

Author Contributions

S. Szalai conceptualized the study, developed the methodology, handled the software development, validated the results, conducted formal analysis, carried out the investigation, provided resources, curated the data, prepared the original draft, reviewed and edited the manuscript, visualized the data, managed the project, and secured funding. B.F. Szívós co-conceptualized the study, validated the results, performed formal analysis, participated in the investigation, curated the data, helped draft the manuscript, reviewed and edited the manuscript, and worked on data visualization. D. Kocsis took charge of software development, validated the results, conducted formal analysis, took part in the investigation, curated the data, helped draft the manuscript, reviewed and edited the manuscript, and contributed to data visualization. M. Sysyn validated the results, participated in the investigation, contributed to drafting the manuscript, reviewed and edited the manuscript, and supervised the study. J. Liu validated the results, participated in the investigation, contributed to drafting the manuscript, reviewed and edited the manuscript, and supervised the study. S. Fischer developed the methodology, validated the results, took part in the investigation, provided resources, contributed to drafting the manuscript, reviewed and edited the manuscript, supervised the study, managed the project, and secured funding. The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed, and approved the final version of the manuscript.

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Conflict of Interest

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Data Availability Statements

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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