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Research Paper

Practice-Focused Evaluation of Paint and Coating Techniques for DIC-Based Surface Deformation Measurement on Biological Skin

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Abstract. This study addresses a key prerequisite for applying digital image correlation (DIC) to quantify surface deformations on biological skin: selecting paints and surface preparation techniques that produce reliable speckle patterns. The goal was to identify practical, skin-safe methods that combine high contrast and pattern stability with accessibility for routine experimental use. Although the aim is human skin testing, porcine skin was used here as a biological analogue. Several coating strategies – including body paints, cosmetic powders, and technical spray coatings – were compared under controlled conditions, with attention to cleaning protocols, storage, and preparation-to-measurement intervals. Performance was evaluated in terms of adhesion, durability, contrast quality, and skin compatibility. Results showed that technical spray coatings yielded the most stable patterns, while cosmetic-based approaches offered gentler application with acceptable accuracy. Validation experiments confirmed that commercially available materials can deliver both precision and safety. The study concludes with practical guidelines for balancing measurement accuracy with ethical and biological considerations, providing researchers with a foundation for reliable DIC measurements on living tissue. These findings also highlight the specific challenges of DIC measurements on biological skin, particularly paint drying and cracking, accumulation in tissue folds, and the influence of skin freshness on measurement reliability.

Keywords: DIC, Surface preparation, Skin, painting techniques, Surface deformation measurement with speckle pattern.

1. Introduction

Digital Image Correlation (DIC) has become one of the fastest-growing and most widely used non-contact optical measurement methods over the last 20 years for analyzing mechanical changes, deformations, and displacements. Its advantages include its non-destructive property, real-time applicability, and the fact that it can be used on materials with complex geometries and inhomogeneities. A key element of the testing method is the random, contrasting pattern (known as a "speckle pattern") applied to the surface being tested, which allows the evaluation algorithms of various measurement systems to track displacements and deformations and determine shape changes. While there is already an extensive literature on the application of DIC to industrial and engineering materials – including metals, composites, polymers – there are still many challenges in adapting the technology for measurements on biological tissues, especially skin. The authors of this article believe that this is because engineers rarely test human samples, while the medical community is believed to lack extensive knowledge of DIC testing. As a test material, skin has particular mechanical and surface properties: it is heterogeneous, elastic, contains moisture, and is porous and non-planar. These properties significantly affect dye adhesion, drying behaviour and pattern durability, all of which have a direct impact on the reliability of the measurement results. It is essential to note that the accuracy of a DIC test result depends on the paint's ability to transmit deformation between the surface of the test specimen and the cameras.

Proper surface preparation and pattern generation are therefore particularly critical steps in the application of DIC when the aim is to accurately measure the deformation of biological tissues, such as skin. In addition, the staining processes used on skin surfaces must meet further requirements: they must be skin-friendly, non-toxic, easy to remove, yet provide a well-adherent and contrasting pattern. This is particularly important if the ultimate goal is to perform measurements on living human skin, for example, in biomechanical, medical, or dermatological research.

The aim of this research is to determine the dyes and surface preparation methods that are most suitable for DIC measurements and can be easily applied in practice on biological skin surfaces. Since studies on human samples are subject to numerous ethical, legal, medical, and technical approvals, which take a long time to obtain and require several supporting studies (as is the case with the present study), the tests are conducted on porcine skin, which serves as a widely accepted model for human skin in terms of morphology and mechanics and is mentioned as an accepted alternative in numerous international publications, as will be discussed below. During the test, the authors of the current paper evaluated several types of paint, various preparation and storage methods, as well as processing times, with a particular focus on practical applicability. When selecting the materials used, it was

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essential to utilize skin-friendly, dermatologically tested, and approved materials. Although this was not necessary for the porcine skin sample, it was a long-term goal for human applicability. The research utilizes only commercially available, easily accessible materials and simple procedures, thereby promoting the widespread dissemination of methods for preparing biomechanical and medical measurements.

It is essential to note that the present research does not employ a medical approach to skin surface paints and is not intended to draw health or clinical conclusions. The studies are conducted from a measurement perspective only, and the applicability of the materials and processes used is evaluated based on Digital Image Correlation (DIC) measurements. The aim of this research is to develop a preparatory measurement methodology that can support future biological skin tissue deformation measurements. The technical question of medical applicability and the conclusions to be drawn are not the subject of this study; they will be investigated in the context of further interdisciplinary research, which will necessarily involve medical experts.

When using digital image correlation (DIC) measurement techniques, a fundamental requirement is to create a high contrast, random pattern on the surface to be inspected, as described in the introduction. However, as no dyes of any kind can be used on human skin due to health risks, the use of safe, skin-friendly body dyes such as Snazaroo is required.

Mihai et al. [1] created this pattern on the soft, cellular silicone samples used in the study using black and white face paint from the Snazaroo brand. The paint was applied with a sponge to a small area in the center of the samples, creating the speckle pattern required for the DIC procedure. The use of Snazaroo paints proved to be advantageous in several respects. On the one hand, the paint provided sufficient contrast on the light silicone surface, which is essential for reliable processing of the images captured by the camera system and for precise tracking of shape changes. On the other hand, the paint is easy to use, dries quickly, and does not dissolve or smudge under load. This is particularly important for soft, elastic materials, where deformations can be significant. The ink is flexible with the sample surface, so it does not affect the measured mechanical behaviour, while ensuring the correct image processing quality. The pattern created with the Snazaroo stain enabled a detailed study of the complex deformation behavior of the cell walls, particularly at the intersections of the cell walls, where local stress maxima were observed. The stability and optical contrast of the speckle pattern were crucial for obtaining experimental results in good agreement with those of finite element simulations.

Schindelin et al. [2] employed the Digital Image Correlation (DIC) technique to investigate the penetration of microneedles into a silicone-based skin substitute, thereby tracking surface deformations. The DIC measurements required the creation of a random pattern on the surface of the silicone with sufficient contrast, which was achieved by applying white and black face paint. Snazaroo brand face paints were used, and the pattern was applied to the silicone surface with a sponge. Using the contrast speckle pattern produced, the process enabled the two cameras of the DIC system to measure the displacement and deformation of the surface as the microneedle penetrated.

Wyatt et al. [3] aimed to record deformations occurring during electrosurgical vessel closure, for which the researchers used the Digital Image Correlation (DIC) technique. This method requires a high-contrast speckle pattern to be applied to the surface under examination, which enables the optical tracking of surface displacements and deformations. The pattern was applied to the outer surface of arteries derived from cartilage after they had been prepared and stretched. The speckle pattern was created by first applying a white base layer with Snazaroo face paint, then sprinkling black makeup powder onto the surface with a makeup brush. The aim was to ensure that both the tissue and the device surface provided sufficient optical contrast for the DIC cameras.

The quality of the painting was checked by a preliminary test run for each sample. Two recordings were taken and processed using DIC software to ensure that the sample application was correct. The test was acceptable if the processing of the images showed no gaps or loss of information in the pattern. A challenge in applying the method was that significant and rapid deformation of the tissue occurred during vessel closure, leading to distortion of the speckle pattern and the appearance of white spots in the images. This made it difficult to generate complete dislocation or stress maps. The research suggests that a DIC system working at a faster image refresh rate could improve this problem, although it would not eliminate it completely, as the high deformation remains a technical limitation.

A growing body of literature exists on the application of digital image correlation (DIC) for measuring human skin, particularly for monitoring skin surface deformation during various mechanical or medical tests. In such research, it is also important to examine why and what measurements are being made by other researchers in the first place, as well as where the science is heading in the field.

The aim of Kao et al. [4] was to determine how human skin responds to very small forces, especially those applied at the tactile sensory threshold. The researchers used von Frey monofilaments of varying strengths (0.02-4.00 g), which were pressed onto the pad of the subjects' index finger, while a three-camera 3D DIC system recorded the skin surface deformations. The DIC was used to accurately measure the depth of penetration, surface elongation and the propagation of deformation around the contact point. Even a force as low as 0.07 g resulted in several micrometres of indentation and significant skin stretching. The data obtained from the measurements were closely in line with the psychophysical perception threshold of the participants. The study demonstrated that the 3D DIC technique can track subtle deformations of human skin in a sensitive and non–contact manner, making it a useful tool for sensory research, neuroresponse studies, skin mechanics and biomedical applications.

Chen et al. [5] present a new multi-view DIC system equipped with a mirror, which enables the complete measurement of 360° shape and deformation of live human skin surfaces. Unlike traditional systems that require multiple cameras, this approach uses only a stereo camera unit and two flat mirrors, allowing it to capture both the front and back of a given body part simultaneously. The essence of the method is that the mirrored views are optically aligned during DIC processing, allowing the shape of the entire skin surface and its deformation fields to be reconstructed during movement. The study demonstrates the applicability of the method using three examples: first, the complete 3D shape of a plastic head was measured; then, the dynamic skin stresses of a woman's facial expressions were analyzed; and finally, the complete circular deformation of a subject's forearm due to muscle movement was examined while the subject clenched his fist. Based on the DIC results, the researchers determined the principal strain directions and values and accurately mapped the skin tension lines. The authors emphasize that this mirror–based DIC method is not only cost–effective but also particularly practical for biomechanical studies of living skin, as it is non-contact, provides full spatial coverage, and is suitable for skin dynamics studies during facial expressions, limb movements, or even medical procedures.

Wei et al. [6] aimed to conduct a dynamic mechanical examination of wrinkle areas on a person's face to understand the biomechanical causes of wrinkle formation. To this end, the research employed a combination of the Facial Action Coding System (FACS) and 3D Digital Image Correlation (3D DIC). FACS was used to standardize the six basic facial expressions (joy, sadness, anger, disgust, fear, surprise) while 3D DIC was used to map the real-time deformation fields (e.g., main strain values and directions) of the skin surface. In the experiment, an irregular speckle pattern was applied to the facial skin as an optical contrast. The participants created the six facial expressions with facial movements, and the DIC system generated three-dimensional displacement and strain fields on the skin fields. Based on these, the authors concluded that wrinkle formation strongly correlates with the directions and

degrees of principal strain. Elaborating on the mechanism of skin wrinkling, the article presents a four–layer finite element model that also includes a muscle layer. This allowed them to investigate how muscle contraction (dynamic wrinkles) and volumetric tissue loss (static wrinkles) contribute to the appearance of wrinkles. The model supports the notion that various skin conditions can result in distinct wrinkle patterns.

Chanda et al. [7] aimed to investigate the biomechanical behavior of wound–damaged skin, particularly to map local overload and crack formation. To this end, they first created biofidelic skin phantoms with various commonly occurring wound geometries (e.g., elliptical, transverse wounds). The samples were subjected to uniaxial tensile testing, while the deformation fields around the wound were quantitatively measured using 2D Digital Image Correlation (DIC). Based on the DIC data, it was possible to observe that the local maximum strains generally occurred on the side surfaces of the wound, while the strain values at the top and bottom were minimal. This was consistent with the geometry of the measurement images and the characteristics of the wound. The experimental results were supported by a finite element (FE) model based on a square-localized elliptical transverse wound geometry. The computational model demonstrated a strong correlation with the strain and stress fields measured by DIC ($R^2 > 0.95$), particularly for the maximum phenomena occurring around the wound.

Medina-Lombardero et al. [8] investigated how the mechanical behaviour of the skin changes during different phases of wound healing using a live mouse model. The researchers monitored the time course of healing at four time points: days 1, 3, 7 and 14. The aim was to quantify the healing process biomechanically using a non–invasive method under physiological (realistic) loading conditions. For the studies, mechanical loads were applied to the wounded skin areas, while surface deformations and strain distributions were measured using digital image correlation (DIC) technology. DIC allowed the researchers to precisely track localised skin stretch patterns around the wound and record them in a map–like fashion at each measurement time point.

Evans et al. [9] aimed to investigate the mechanical properties of living human skin (on the back) without contact, using 2D DIC and finite element (FE) modeling. The researchers performed uniaxial tensile tests while recording skin surface deformation using speckle patterns and DIC technology. Based on the displacement and strain data obtained in this way, an Ogden–type hyperelastic FE model was fitted. The measurements revealed that the skin's behavior is direction-dependent (anisotropic), and tests performed along Langer lines confirmed this. The method was suitable for the quantitative determination of skin elasticity, tensile strength, and energy absorption. The research demonstrated that the combination of DIC and FE modeling can be effectively used for the in vivo mechanical characterization of human skin.

Lionello et al. [10] aimed to develop a reliable and easy-to-use method for generating speckle patterns suitable for digital image correlation (DIC) measurements on biological soft tissues, such as skin or tendons. Since soft tissues are often highly deformable and their surfaces are wet or irregular, generating speckle patterns on these materials is particularly challenging. The authors aimed to present a method that not only produces a clearly visible and traceable pattern but also does not adversely affect the mechanical properties of the tissue. The proposed method consisted of two steps: first, the tissue surface was stained with a saturated methylene blue solution to obtain a uniformly dark background color. Then, white airbrush paint was applied to spray a fine, random speckle pattern onto the surface. The resulting contrasting pattern met the DIC requirements, i.e., it produced clearly recognizable, unique patterns. The method was tested on 40 porcine ligaments, which were subjected to cyclic tensile testing. Deformations were recorded using DIC, and the traceability of the sample and the effect of speckle on the mechanical behaviour of the tissue were evaluated. According to the tests, the pattern was well traceable on 96% of the total surface, and the sample remained stable even after repeated large deformations (30 cycles, 10% elongation). The differences measured in the stiffness and tensile strength of the tissues were not statistically significant, meaning that the dye did not alter the biomechanical properties of the tissue. The authors concluded that the procedure is simple, cost-effective, and can be applied to any type of soft tissue. Although the tests were performed on animal tissue rather than human skin, the method appears to be adaptable to human skin, especially if the base colour and contrast dye are selected appropriately for different skin colours.

Dalle Mura et al. [11] aim to objectively measure the pliability of burn scars using Digital Image Correlation (DIC) technology. In DIC, the displacement and deformation of the skin are calculated by comparing two digital images of the skin, one at rest and one deformed. This requires a random, high-contrast speckle pattern on the skin surface, which provides a well-traced texture for the image processing algorithm. The pattern is created with black dots on a white background using a spray technique with water-based paint, ensuring that the skin or silicone samples are not damaged. The optimal speckle dot size is approximately 3–5 pixels. The system uses an electric actuator and pressure sensor to apply a controlled force to the skin surface while the cameras capture images. These images are processed by open-source MATLAB–based software. The system can reliably distinguish between materials with different elasticities and provides repeatable measurements, making it a promising tool for clinical scar analysis.

Cheng et al. [12] apply the 3D digital image correlation (3D-DIC) method for the dynamic analysis of facial expressions, which enables the measurement of three-dimensional displacements and strains of the facial surface with high accuracy. For the analysis, a speckle pattern is painted on the face, providing a random, highly recognizable texture in the images that allows the DIC algorithm to track facial features reliably. The authors analyzed six basic facial expressions (e.g., joy, anger) and identified two key regions: the S-region (where movement starts) and the F–region (where the largest deformation occurs). Strain fields are particularly well-suited to detect local muscle movements, providing an objective and quantitative view of the subtle dynamics of facial expressions. The method is non-invasive and offers high temporal resolution, opening up new possibilities for facial analysis.

As human trials have many of the limitations previously discussed, a key research question is which skin tissue models – such as those derived from animals or synthetic materials – are suitable for preliminary testing.

Riviere [13] provides a detailed analysis of the suitability of porcine skin as a model for human skin research. According to the authors, there are significant similarities between the two skin types at the anatomical, physiological, and biochemical levels. They emphasize that porcine and human skin are similar in terms of thickness and structure, both having well-developed epidermal layers, papillary and reticular dermis, and subcutis. The arrangement of collagen and elastin fibers is also similar. According to the article, porcine skin is a suitable model for research in areas such as wound healing, various dermatological and cosmetological developments, and toxicological testing. Immunological responses, pigmentation characteristics, and transdermal absorption are also comparable to those of human skin in many cases. In addition, it has the practical advantage of being easily accessible and usable over a large surface area. However, the authors emphasize that its use as a model always depends on the specific research question at hand. Certain differences (e.g., location of sebaceous glands, hair follicle density, and regional variations) may affect the transferability of the results. Overall, the study concludes that porcine skin is one of the most suitable animal models for human skin research, particularly when human samples are unavailable.

The aim of Ranamukhaarachchi et al. [14] was to directly compare the mechanical properties of human and porcine skin in fresh condition and after one cycle of freezing at –80 °C. Both types of leather were tested at two relative humidity conditions (35% and 100%) using microindentation testing and microneedle insertion, rather than tensile testing. The microindentation measurements revealed that the mechanical properties of bulk skin, particularly the stratum corneum, differed significantly between human and porcine skin, and both were affected by freezing: Young's modulus changed in opposite directions for the two

skin types. In contrast, the local in–plane mechanical properties (e.g., insertion force and displacement) during microneedle insertion, although also variable, were more comparable between human and porcine skin, especially at high humidity and in fresh condition. The researchers found that freezing had different effects on the two skin types: the modulus of the human stratum corneum decreased, while that of the porcine skin increased, bringing the modulus of the frozen porcine SC closer to that of fresh human SC. In its fresh state, human skin was stiffer than porcine skin. The study provides insight into when porcine skin can be considered a good substitute for human skin, for example, in microneedle tests, especially with fresh samples and high humidity, while it is not recommended for bulk mechanical property testing. However, they emphasize that these results are important guidelines for selecting the appropriate skin sample type for different applications.

The aim of Krehbiel et al. [15] is to use digital image correlation (DIC) to more accurately detect the borders of basal cell carcinoma (BCC). Since the tumor is much softer than healthy skin, strain concentrations develop in the tumor area under strain, which can be well detected by DIC. The researchers used gelatin skin replicas and pig skin as models, in which inclusions of different shapes and stiffnesses (to simulate the tumour) were inserted. The samples were stretched, and surface deformation was monitored using DIC. For the DIC to work, each sample was provided with a black speckle pattern applied uniformly with India ink. DIC analyses were able to determine the edges of inclusions with an accuracy of up to 2–19%, which is significantly better than the current surgical margin of safety. The method is simple, inexpensive, and non-invasive, and could be a promising technique for detecting BCC, even in real skin.

When reviewing the literature, it is essential to consider whether the skin surface alone is suitable for analysis using DIC, and whether skin patches (e.g., freckles) are suitable for tracking deformation.

Cheng et al. [16] investigate how to accurately measure the deformation of biological skin based on its natural texture, without the use of artificial speckle patterns. The optical method used in this study is digital image correlation (DIC), which typically requires speckle patterning. However, the authors have developed a speckle-free version, known as SF DIC (speckle-free DIC), that tracks the skin's own patterning elements. Several pre-processing steps were applied in the preparation of the method: Gaussian filtering for noise reduction, blob detection to find the characteristic pattern locations of the skin, self-adaptive subset size selection for optimal tracking accuracy, and high support interpolation for proper tracking. These are combined with a selective computational strategy that enhances efficiency without compromising the accuracy of the results.

In addition, the authors analyzed the optical properties of the skin and found that blue LED lighting provided the best contrast and pattern tracking. The study involved three physical experiments. Two experiments were conducted on porcine skin: one sample had artificial speckle, while the other had only natural texture. The SF DIC results closely matched those of conventional speckle-based DIC in terms of both deformation and stress field, demonstrating the reliability of the new method even without speckle. The third experiment was conducted on live human skin (in vivo), confirming that SF DIC is functional and accurate in a real biological environment. According to the authors, the SF DIC method offers an excellent alternative to traditional DIC, as it eliminates the need for artificial speckle, allows for simpler preparation, and can be used in vivo on living skin. They also mention the examination of the deformation of other materials with natural textures as a potential area of application.

It is also important to consider how biological skin samples should be stored, as measurements can often take several days to complete. In conventional engineering applications, this is not a problem, as metals can be stored at 20°C and 50% RH humidity for long periods of time. For "pre" samples, however, there is a possibility of "ruin" very quickly.

Skin storage is crucial in the treatment of burn victims and other surgical patients, as fresh skin is not always available. The goal is to preserve the viability or structural integrity of the skin tissue for as long as possible for later use. For live, viable skin, the most common method is cooling at 4°C, which ensures usability for a maximum of 3–7 days [17]. For longer storage, freezing at –20 °C or cryopreservation (–80 °C or –196 °C) can be used [17]. The addition of cryoprotective agents (e.g., DMSO, glycerol) prevents ice crystal formation and aids cell survival [17]. Skin can be stored at –20°C for approximately 2 months, while it can remain viable for up to 5 years in liquid nitrogen [17]. Thawing is performed quickly at 37°C to avoid cell-damaging crystal formation [17]. For non-viable skin (where living cells are not necessary), several preservation methods are available: glycerin preservation, glutaraldehyde fixation, lyophilization (also known as freeze drying), and radiation treatment. These methods preserve the tissue's structure while destroying microorganisms and reducing the immune response. The choice of storage method depends on the purpose of use, the required duration, and the available infrastructure. The study provides a detailed description of the physical and chemical background of each procedure, its practical implementation, and its impact on cell viability.

Ben-Bassat et al. [18] aimed to determine the maximum storage time of cryopreserved human skin (cadaveric split-thickness allografts) that remains functional for skin grafting. Skin samples were prepared using programmed freezing (1 °C/minute) and then stored in liquid nitrogen for 5, 6, or 7 years. The studies showed that graft performance gradually declined during long-term storage, as indicated by deterioration in histological characteristics (e.g., epidermal integrity, dermoepidermal junction, collagen organization, graft adhesion). Nevertheless, the transplantation performance of skin stored for 5 years did not show a statistically significant deterioration compared to fresh skin. In the case of skin stored for 6 years or longer, the deterioration was already significantly detectable in all parameters examined. Based on linear regression analysis, no significant correlation was found between storage time and histological quality up to 65 months of storage, confirming that cryopreserved skin can be used safely for up to 5 years.

Holzer et al. [19] investigated the long-term storage of split-thickness porcine skin grafts using cryopreservation. The researchers compared freshly frozen skin samples (stored for 15 minutes) with samples stored in liquid nitrogen (–196 °C) for more than 7 years. The grafts were implanted into partial-depth wounds on the backs of MHC-compatible porcine models and then evaluated for function using clinical, histological, and cell viability (MTT assay) tests. The results showed that the function of long-term stored skin was fully comparable to that of fresh grafts, with no significant differences in integration, cell viability, or tissue structure. The study confirms that, with proper preparation, porcine skin can be stored for more than seven years using cryopreservation without compromising its biological usability. This method offers an effective solution for skin banks and experimental models.

Based on the current literature review, it is also essential to briefly address the legal regulation of DIC (Digital Image Correlation) measurement technologies on human skin samples. Although the legal aspects are not strictly within the scope of this article or journal, their presentation will contribute to a full understanding of the subject.

Ethical and legal regulations governing human tissue research, particularly the EU Tissue Directive (2004/23/EC) and its implementing regulations [20–23], require strict ethics committee approval, donor consent, and the use of only authorized facilities.

The Declaration of Helsinki and the CIOMS guidelines [24] outline the fundamental principles of ethical research involving human tissues, including the protection of participants, voluntary consent, and the principle of subordination to the research aims. They also stress respect for the rights and dignity of participants and transparent regulation of the use and storage of biological samples [24].

The use of human tissues for research is also subject to strict ethical and legal regulation in Hungary. Government Decree 235/2009 (X. 20.) on "Medical Research Involving Human Subjects" [25] states that such research requires the approval of the relevant ethics committee (ETC TUKEB or regional ethics committee), detailed documentation of the research design, and written informed

consent and voluntary agreement of the participants. The Code of Bioethics issued by the Health Sciences Council [26] emphasizes that biomedical research should only be conducted in duly authorized institutions and under regular ethical supervision. The Code emphasises the protection of participants and the legality of the research environment.

The Materials and Methods section of this paper will proceed with a description of the test specimen materials used, the paints tested, the tools and standards employed, and the methods and procedures used. This Section is followed by the Results and Discussion section, in which the results of the tests are presented and, on a test-by-test basis, explanations of these results are given, together with, where possible, some insights into future objectives. The concluding Conclusion section provides a summary of the article and the conclusions drawn.

2. Materials and Methods

The aim of the research was to examine commercially available body paints. During the examination, body paint was utilized, as it is suitable for use on human skin due to its skin-friendly properties. This section describes the experimental materials used in the experiment ("porcine skin"), paints, measuring instruments, and the various paint tests.

2.1. Specimen (porcine skin)

Based on the results of literature research, porcine skin was used for the test samples. Fresh porcine skin samples were obtained from a local butcher, thus ensuring that the samples were no more than 3 days old at the time of slaughter. During transport, the traders stored the products at a temperature of 0-4°C. For the test, skin from two anatomical regions was applied: back skin covering the shoulder and rib area, and skin from the lower abdomen.

2.2. Surface preparation, materials and processes

The porcine skin arrived from the butcher, containing meat and fat tissue that had to be removed before examination. First, the remaining muscle tissue was removed with a knife, then the fat layer was also separated with a sharp knife, leaving only the raw skin for further preparation. The skin was prepared in this way and then cut into uniform 20x90mm strips. As the skin is extremely flexible and greasy in this state, a cutting error of 3-5mm and a slight deviation from strict parallelism along the sides was permissible.

The effect of storage was also investigated, and the samples were divided into three groups. The first group consisted of "fresh" samples, chilled only, to be used immediately. The second group was stored in the freezer for 1 week, while the third group was frozen for at least 1 month. This experiment was conducted to investigate the impact of sample storage on their usability and to determine the optimal timing for measurements in such experiments.

Prior to staining, the samples were cleaned uniformly with warm water (34-36°C), and an antibacterial liquid hand wash soap (Dettol Antibacterial Hand Wash, Reckitt Benckiser Group, pH 5.5) was used for degreasing. Subsequently, before staining, the surfaces of the samples were uniformly coated with 99.8% pure pharmacopoeial standard (2-Propanol, Ph. Eur. 11.0, ≥99.8% purity, diluted to 70% v/v with distilled water) isopropyl alcohol to remove all fat from the skin.

2.3. Paints

In preparation for the DIC measurement, a contrast speckle pattern is applied to the surface under test. To create this, four different light shade primers (white and light grey: P4, P5, P7, P8) and five different dark shade primers (black and dark blue: P2, P3, P5, P6, P8) were tested to create a random speckle pattern and a uniform base colour (Table 1).

The primers needed to be tested because, as clarified earlier, the long-term goal is to measure them on human skin, where samples with darker pigments are also present. It is already known from engineering experience that DIC systems used in engineering practice detect black stain patterns on white (light) backgrounds more easily, and the authors of this article have similar experience in this area.

Only commercially available, tested and dermatologically approved products have been selected, so all the dyes used in this article are cosmetic products and comply with the EU Cosmetics Safety Regulation (EC) No 1223/2009.

2.4. Surface preparation for DIC, painting

The samples must be dyed in order to perform DIC (Digital Image Correlation) measurements. For accurate repeatability, a well-established method was employed in this case as well. The white base coat was applied to the skin surface with a brush in an even layer, thick enough to cover the natural color of the porcine skin. A brush was also used to apply the black dots, using the ends of the brush bristles to create a discrete, randomly distributed spot pattern by touching the surface perpendicularly. This was necessary because these paints are not liquid but paste-like, so they cannot be applied to the surface by spraying. Henna paint was an exception, as its packaging allowed the dotting technique to be applied without a brush, in a similar way to dotting with a marker pen.

During the research, it is essential to determine the thickness of the applied paint layer. This can be done while the paint is still wet, not when it is dry. The Elcometer 112Al wet film comb (Fig. 1) was used for the test. The measurement is in accordance with ISO 2808:2019 - Paints and varnishes - Determination of film thickness [27]. Immediately after painting, the comb of the testing instrument is pressed into the wet paint, and the thickness value in microns (i.e., 10^{-6} m) is read off the side of the instrument by highlighting it. The measurement should be taken three times per test specimen and the results averaged. The measuring range of the instrument is 25-3000 micrometres [27].

Table 1. List of paints used.

ID	Name	Producer	Color
P2	Instant Henna-Paste	TyToo	-
P3	Face Paint	Snazaroo	Dark Green
P4	Face Paint	Snazaroo	Light Grey
P5	Face Paint Kit (5 colors)	Snazaroo	Black and White
P6	Face And Body Make-up Paint	Jovi	Black
P7	Face And Body Make-up Paint	Jovi	White
P8	Face Paints Set (4 colors)	EberhardFaber	Black and White

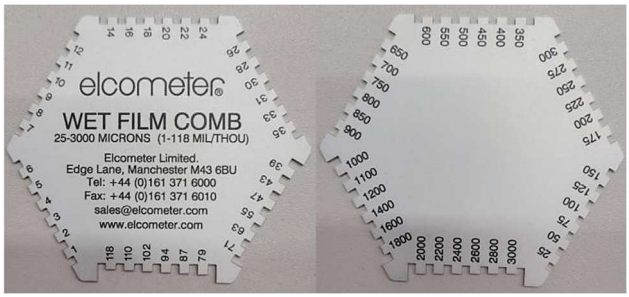

Fig. 1. Elcometer 112Al wet film comb.

Fig. 2. Elcometer 107 Cross Hatch cutter.

2.5. GOM Aramis

The tests were performed with the GOM ARAMIS 5M DIC system. The GOM ARAMIS 5M is a high-precision, non-contact optical measuring system based on the principle of digital image correlation (DIC), specifically designed to measure very small homogeneous deformations of less than 0.1% [28]. The system utilizes two synchronized 12-megapixel industrial cameras with 50mm lenses and polarizing filters, mounted on a rigid frame in a position nearly perpendicular to the specimen surface.

The method is based on a black-and-white speckle pattern of 3-5 pixels in diameter with approximately 50% coverage applied to the surface under test, which allows tracking the movement and deformation of the surface with subpixel accuracy. The quality of the speckle pattern (contrast, speckle size, distribution) has a major impact on the measurement accuracy. The two cameras simultaneously record and analyse the displacement and distortion of the specimen using special algorithms. A key element of the measurement system is the calibration performed before each measurement, as well as the selection of optimal image processing parameters [28].

The ARAMIS 5M records at 25 frames per second at maximum resolution; however, by reducing the resolution, the sampling rate can be increased to allow for the investigation of fast processes [29]. During the measurement, the cameras cannot be moved, so only one side of the object under test can be seen at a time, which can be a limitation in accuracy for asymmetric deformations. It has the advantage of being able to record the entire deformation process without interruption, making it suitable for real-time dynamic tests. Proper preparation (staining, lighting, calibration) is key to reliable results.

2.6. Test of paint(ing)s – Touch test

The minimum drying time of painted test specimens shall be determined by a subjective, tactile test procedure [30]. The purpose of the Touch Test is to determine when the paint has dried to the point where the surface no longer leaves a mark when touched, allowing the laboratory operator to move the specimens. After staining, the test specimens are touched with rubber gloves every five minutes, and then visually inspected to determine if any trace of the stain remains at the point of contact. If a stain remains, the test shall be repeated after a further five minutes. The test specimens shall be considered sufficiently dry when the contact no longer leaves a dye residue; the specimens may then be safely moved and further measurements made.

2.7. Test of paint(ing)s – Print-free test

This test method is used to determine when the paint layer is dry enough to be loadable but still retains the necessary elasticity, i.e., not fully cured. The method is based on ISO 9117-6:2012 - Paints and varnishes, Drying tests - Part 6: Print-free test and ISO 9117-5:2012 - Paints and varnishes. Drying tests - Part 5: Modified Bandow - Wolff test [31,32], but modified concerning the loads applied. The reason for using these two standards, or slightly modifying them, is that the use of fully dried paint for DIC tests should not be allowed based on literature and practical experience, as the paint, if no longer elastic, cannot convey the deformation of the test specimen being measured. The test is performed by placing a 26 mm diameter, 80 g/m² paper disc on the painted surface, on which a 22 mm diameter, 5 mm thick, 50 IRHD hardness rubber sheet (ISO 7619) is placed. Weights of 20 g, 200 g, 500 g and 1000 g are placed successively on top of the paper disc, each for 60 seconds. After the given loading time, the test impactor shall be impacted against a 30 mm thick solid wood surface from a height of at least 20 mm. If the paper peels off the paint, the next weight is applied; if it sticks, the test is repeated after 15 minutes. The paint passes the test if it can withstand a load of 1000 g without the paper sticking to it. The method only evaluates the load capacity and does not provide information on the adhesion properties of the surface, therefore, an adhesion test is required.

2.8. Test of paint(ing)s – Cross-cut test

At this stage, a standard cross-cut test is performed in accordance with ISO 2409:2020 - Paints and varnishes – Cross-cut test [33]. According to the cross-cut test standard, the test must be performed using an Elcometer 107 Cross Hatch cutter with a 6×2mm test head (Fig. 2). The test determines whether the paint adheres sufficiently to the surface after tack-free drying, i.e., whether it exhibits shape-changing properties. The tests must be carried out after the print-free drying times. During the test, 6-6 parallel scratches perpendicular to each other are made with a cutting head corresponding to the layer thickness, and then the layers loosened by the cut are removed with an adhesive strip of standard adhesion strength. When evaluating the samples, it is important to note whether there are any signs of paint peeling along the grid cuts after removing the adhesive strip. To classify the samples, the results must be classified into one of the categories ranging from 0 to 5 specified in the standard using a comparative method.

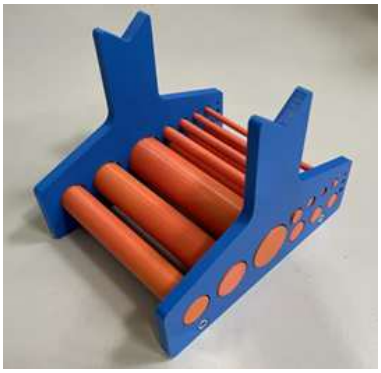

Fig. 3. Bending device.

Fig. 4. Experimental setup – GOM ARAMIS 5M and Erichsen Cupping Test Machine.

2.9. Test of paint(ing)s – Modified bending test

During the bending test, the painted plates were tested using a 10 mm diameter roller (Fig. 3). The 3D-printed plastic bending device was manufactured by the authors. The purpose of this measurement was to assess the ductility and adhesion of the paint layer. The test procedure was based on ISO 1519:2011 - Paints and varnishes - Bend test (cylindrical mandrel) and ISO 1518-1:2023 - Paints and varnishes - Determination of Scratch Resistance - Part 1 [34,35]. Preliminary experiments in this research revealed that, in some cases, the paint layer appeared intact on visual inspection after bending; however, it partially detached from the specimen's surface, thereby not providing a proper conveyance of the deformation parameters of the specimen. Combining the bend test with the scratch test enabled the identification of this phenomenon. The test was carried out after the catch-proof drying.

For the test, the 20×90 mm dyed skin sample shall be scratched in the middle with a scratching needle, preferably with the dye layer completely cut through. The 10 mm bending roller is then used to bend the skin 180°. When evaluating the results, the following classification criteria shall be given:

1. After bending, the paint does not separate from the surface along the cut;
2. After bending, flaking and slight cracking are observed along the cut;
3. After bending along the cut or anywhere the paint separates from the surface, no adhesion or contact.

2.10. Experimental setup, DIC calibration

The Erichsen test plays an important role in the research. Skin samples must be loaded, stretched, and examined in a controlled and reproducible manner. The test needed to be slow enough to cause significant deformation, yet still allow for visual inspection of the measurement and the behavior of the dyes during the process. The Erichsen test, already known in sheet metal forming, proved to be a suitable choice for this purpose. The test and the tools used comply with the ISO 20482:2013 Metallic materials – Sheet and strip – Erichsen cupping test standard. The measurement was performed on a hydraulic Erichsen testing device with a 20 mm diameter test die and a fixed binder force of 1.0 kN. During the fixed binding, the die and the blank holder must be pressed together so tightly that the leather sample cannot slip between them, allowing the material to stretch only. However, this force must not be too high, as this will cause the leather to be sheared. This was determined through test compressions. The test is carried out uniformly up to a die displacement of 30 mm with a punch speed of 3 mm/s. During the measurement, the GOM ARAMIS 5M DIC system, positioned above the test area, records the deformation of the specimen with a sampling frequency of 9 Hz. When the results are evaluated, the displacement measured on the equipment (30 mm) is compared with the displacement values measured by the GOM, thus validating the results. During the GOM evaluation, the quality of the point cloud achieved by the paints is also checked. In this test, the quality of the 3D point cloud (discontinuous, pitted, or continuous uniform) produced by the stain pattern is checked. This is important because a defective or incomplete point cloud will result in data loss, which will reduce the evaluation of the measurement. The experimental setup is shown in Figure 4 [36].

Fig. 5. Top left fresh, bottom left frozen for one-week, right samples frozen for at least 1 month.

Fig. 6. Visualization of blisters on porcine skin.

3. Result and Discussion

Accurate and reliable DIC analysis begins in advance of the measurement. Every step, from sample storage to surface preparation, prior to each measurement, affects the quality of the measurement. This Section presents and interprets the results obtained during the tests in the logical order of the experimental workflow: sample storage and preparation, evaluation of dye performance, and DIC measurement results. The Section highlights how each step impacted measurement accuracy and data quality, laying the groundwork for the conclusions presented in the next Section.

3.1. Sample storage and preparation

As described in section 2.2, the porcine skin samples were divided into three groups. The first group consisted of "fresh" samples that were only refrigerated and used immediately, the second group spent one week in the freezer, while the third group was frozen for at least one month (Fig. 5). A control sample was prepared for each sample, from which the fat layer was not removed.

In the case of the sample that spent one month in the freezer, blisters appeared on the surface of the skin, as shown in Fig. 6. This indicates that the skin suffered frostbite and lost a significant amount of its elasticity. Similar spots appeared on the control sample, but the sample remained significantly more elastic than the treated sample. One week of freezing caused similar, minor surface changes, resulting in a noticeable color difference compared to the fresh sample. Based on these results, it can be concluded that measurements should be taken after a maximum of 1 week of storage in the freezer. Samples without a fat layer stored only in the refrigerator hardened completely after 8 hours, while samples stored with a fat layer showed such changes only after 24 hours.

During this experimental phase, the length of time that the thawed and prepared samples could be stored in the open air was also investigated. It was uniformly observed that after 4 hours, the samples without fat tissue became completely hard, regardless of how they had been stored previously. The control samples with fat tissue did not exhibit such a change; however, after 24 hours, they emitted an extremely unpleasant odor. These tests indicate that the prepared sample must be examined within 4 hours; however, even with fat tissue, preparation and measurement must be initiated within 24 hours. These results confirm that experiments on natural skin tissue require careful timing and preparation.

3.2. Results of Paint Performance Tests

In this subsection, the results of the painting tests are presented. There was already extensive experience with paint testing on sheet materials, so the research began here using these methods and the logic described in Section 2.

Unfortunately, however, the touch test results showed early on that these paint groups behave quite differently from the industrial paints tested previously. Using the Elcometer 112Al wet film comb, the thickness measurements of the brush-applied paint samples are presented in Table 2.

Table 2. The result of the paint layer thickness measurement ("Avg." means average).

ID	Name	Producer	Color	Avg. Thickness [μm]
P2	Instant Henna-Paste	TyToo	-	283
P3	Face Paint	Snazaroo	Dark Green	165
P4	Face Paint	Snazaroo	Light Grey	150
P5	Face Paint Kit (5 colors)	Snazaroo	Black and White	125
P6	Face And Body Make-up Paint	Jovi	Black	170
P7	Face And Body Make-up Paint	Jovi	White	155
P8	Face Paints Set (4 colors)	EberhardFaber	Black and White	185

Table 3. Result of the Touch Test.

ID	Name	Producer	Color	Drying after 24h	Drying after 48h
P2	Instant Henna-Paste	TyToo	Dark Brown	OK	OK
P3	Face Paint	Snazaroo	Dark Green	NO	OK
P4	Face Paint	Snazaroo	Light Grey	NO	OK
P5	Face Paint Kit (5 colors)	Snazaroo	Black and White	NO	OK
P6	Face And Body Make-up Paint	Jovi	Black	OK	OK
P7	Face And Body Make-up Paint	Jovi	White	OK	OK
P8	Face Paints Set (4 colors)	EberhardFaber	Black and White	OK	OK

The results also show that these paints can be applied by brushing to an acceptable thickness, thereby avoiding the need for excessive amounts of paint.

However, after thickness measurement, these paints exhibited very different behavior from the acrylic paints applied by spray or airbrush in the authors' previous research. They did not dry completely, even 5 hours after painting, and left a continuous stain on the rubber gloves. None of the paint types tested dried on the leather surface. The exception to this was henna (P2), which, according to the manufacturer's specification, dried completely and uniformly captured the surface of the skin tissue 30 minutes after staining.

However, the other dye types and all the manufacturers' products did not dry. At this stage of the research, the painted samples were left for 24 and 48 hours. The results were as follows (Table 3).

The paint manufacturer's goal is to address this phenomenon. Presumably, the reason this type of paint does not dry on the skin is that it follows the movement of the wearer's skin, mimics the wearer's facial expression, and does not peel off, dry, crack, or fall off the surface. This feature can also be an advantage when making a DIC measurement. The P3, P4, and P5 dyes dried onto the skin tissue sample surface 48 hours after dyeing, while the others dried 24 hours after dyeing. This occurred to the extent that they cracked at the slightest movement on the surface. At the same time, the painted skin samples also dried out in the open air, as confirmed by previous tests. From this result, it can be concluded that DIC experiments with such dyes should be carried out within 24 hours of dyeing. The henna (P2) dye, of course, is an exception to this.

In light of these findings, it is not feasible to perform the Print-free test or the Cross-cut test. The necessary tests were, of course, tried. However, due to the wet consistency, the paper circles were constantly stuck to the surface during the print-free test, so that they adhered to the ink even with the smallest load. In the cross-cut test, the adhesive tape continued to pull the paint off the surface.

However, the advantageous properties of the paints are evident in the modified bending test, where all paints were rated 1 (the paint does not separate from the surface along the cut after bending). This result was very encouraging before the DIC measurements were started.

It can therefore be concluded that, although the given dyes do not dry on the surface of the skin tissue within 24 hours, they do not separate from the surface even when bent along a small radius along a cut layer of dye, and thus presumably mediate the deformation of the sample well.

To ensure the experiment's completeness, the behavior of the dyes on skin tissue subjected to various storage methods was examined. This included assessing whether the elasticity of the skin tissue affected the dye and whether blisters formed on its surface. The Erichsen testing device was used for the experiment to observe the behavior of the dyes in a controlled manner. The test was performed as described in Section 2.10, with the exception that the DIC system was not yet used here. During the process, light-colored primer paints with IDs P4, P5, P7, and P8 were tested. The results of the tests are shown in Fig. 7, where the samples for each paint are listed from left to right as follows: (a) fresh, (b) frozen for 1 week, (c) frozen for 1 month.

It is clearly visible that no stain sample was taken, as only possible paint adhesion defects were detected, for which a stain sample is not necessary. It was found that the paints can also provide good adhesion on dried or blistered samples, which is shown in Fig. 7. It is also observed, however, that there are some dyes that, after dyeing, tend to collect more in the natural folds of the skin tissue, while the rest of the dye is deformed with the skin. This breaks the uniform contrast, which can cause errors during the DIC measurements when making the point cloud. The exceptions to this were the P4 and P5 paint samples; it is clear from the images that the paint remained uniform at the end of the deformation, with no white "streaks" forming on the surface. This phenomenon is presumably due to the consistency of the paints, similar to the way different cosmetic products behave on the skin.

This is not a problem in principle, but the fact that some paints are more embedded in the surface cracks of the skin may result in different 'whiteness' areas, which may cause contrast differences that should be avoided.

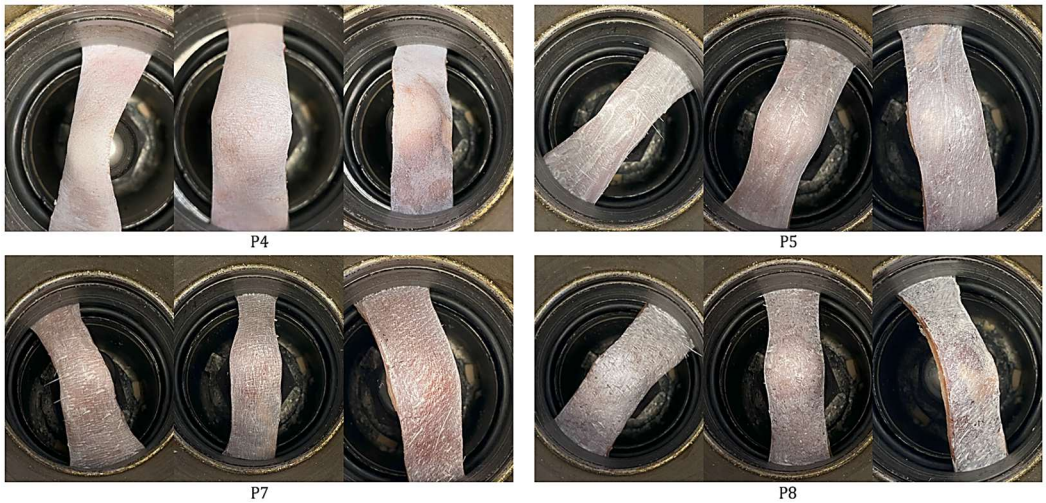

Fig. 7. Results of the Erichsen test. For paints P4, P5, P7 and P8, the samples from left to right are as follows: (a) fresh, (b) frozen for 1 week, (c) frozen for 1 month.

Fig. 8. In the case of fresh samples, the stochastic speckle pattern with the following paints: P2 - big, P3, P5, P6, P8, P2 – small.

3.3. Results of DIC Measurements

The next phase of the research was DIC measurement. Here, the stochastic speckle pattern was applied to the surface as described in Section 2. To achieve the best possible results, only fresh skin tissue was used in this study. After applying a light base coat (the white paint that performed best in the previous subsection, P5, was used uniformly for the base coat), the speckle pattern was created with dark paints, an example of which is shown in Fig. 8.

It is essential to reiterate that the test serves a dual purpose in conjunction with DIC measurement, which should be taken into consideration throughout. During the measurement, it is necessary to validate which dye best reflects the die displacement, i.e., the 30 mm die displacement, of which the actual deformation phase is 17±0.1 mm (the ±0.1 mm represents the verified stopping accuracy of the machine). Perhaps even more importantly, it must be determined which painting method provides the most detailed point cloud, as future research will require the measurement of even the smallest skin deformations, which is only possible with a virtually flawless point cloud.

The displacement of the die in the deformation zone was therefore uniformly 17 +/-0.1 mm. The displacement values recorded by DIC measurement must be compared with the results shown in the following table (Table 4). The values in the table are the average of three measurements.

The results of the measurements confirm quite well the statement made at the end of the previous subsection, according to which paints that do not dry completely will convey the shape change of the tested sample well. It is clear that most paints show a deviation of less than 2%, which can be considered a very good result for this type of measurement setup. In fact, two paints (P6 and P8) measured values within the machine's stopping error. The deviations of more than 5% in samples P3 and P5 are not ideal, in which case accuracy above 0.1 mm is still sufficient, but they cannot be used for smaller displacements, more detailed displacement measurements, or stress mapping. It is also interesting to note that, although the paints were applied using the same technique and brush, they exhibited different behavior. Here, P6, P8, and P2 henna paints were the easiest to use for creating spot patterns. Although this is a subjective observation, the authors believe it is an important point from the user's perspective.

After examining the shifts, the evaluation of the deformation point cloud obtained using the speckle patterns remains at the end of this research. This is one of the most crucial factors to consider when evaluating a paint or painting method. If the quality of the point cloud obtained with the speckle pattern is inadequate, important details may be lost, or even the entire research may become fruitless. A point cloud is of good quality if there are minimal gaps, breaks, or holes throughout the deformation or examination process. Most DIC systems, if they cannot follow the movement of a given point cloud detail (inspection window) from frame to frame, will skip that area from the measurement, i.e., an empty part or hole will appear on the surface. The resulting gaps will not provide any evaluable measurement data or results. If this is in a critical location from the perspective of a given research, the entire investigation becomes inefficient. Of course, DIC software is capable of compensating for these gaps, i.e., interpolating the mesh; however, each such operation introduces increasingly greater errors into the measurement. Therefore, the better the quality of the speckle pattern, the fewer errors occur in the point cloud, which means that the software requires fewer corrections, resulting in more accurate and detailed results. Fig. 9 shows the results for bad (left) and good (right) conditions.

Fig. 9 illustrates and interprets the results. The figures clearly show what happens when a point cloud is inadequate, falls apart, or develops holes. A good example of this is the point clouds of the P2 samples, which fell apart completely at the end of the deformation. Although they still contain the maximum displacement (the point cloud was faulty in the given sample in such a way that the peak still provided data), they cannot be used to interpret the total surface deformation, or can only be used to a limited extent. It can be seen that holes also formed in the P8 sample, but these are significantly smaller, covering less than 1-2% of the total surface area. During the DIC point cloud analysis, the P8 and P6 paints performed best, but the P5 and P3 paints also showed a 6-8% deficiency over the entire surface (the percentage values can be read from the GOM ARAMIS software).

Unfortunately, the assessment of these results is subjective, as it depends on the research's purpose. In other words, if the goal is only to determine the maximum displacement, then even a completely fragmented point cloud at its peak can give good results, which is obviously completely useless for determining the deformation map of an entire surface. In this research, the authors set the goal of complete surface "measurability," so the paints were ranked with this in mind. During the research, values below 10% received an acceptable rating. In the case of such errors, the point cloud can still remain sufficiently detailed, and the data can be used, thus allowing results to be obtained from the individual tests. The results are summarized in Table 5.

Table 4. Results of DIC Measurements.

ID	Distance from DIC [mm]	Distance from movement [mm]	in Tolerance	Deviation [%]
P2 – small	17.293	17±0.1	+0.193	1.694
P2 – big	17.285	17±0.1	+0.185	1.648
P3	18.211	17±0.1	+1.111	6.649
P5	17.898	17±0.1	+0.798	5.017
P6	16.963	17±0.1	inside	0
P8	16.97	17±0.1	inside	0

Table 5. Results of Mesh quality ("Avg." means average).

ID	Avg. surface defect [%]	Acceptable surface defect [Yes/No]
P2 – small	42.6	No
P2 – big	69.4	No
P3	7.3	Yes
P5	6.9	Yes
P6	2.1	Yes
P8	1.4	Yes

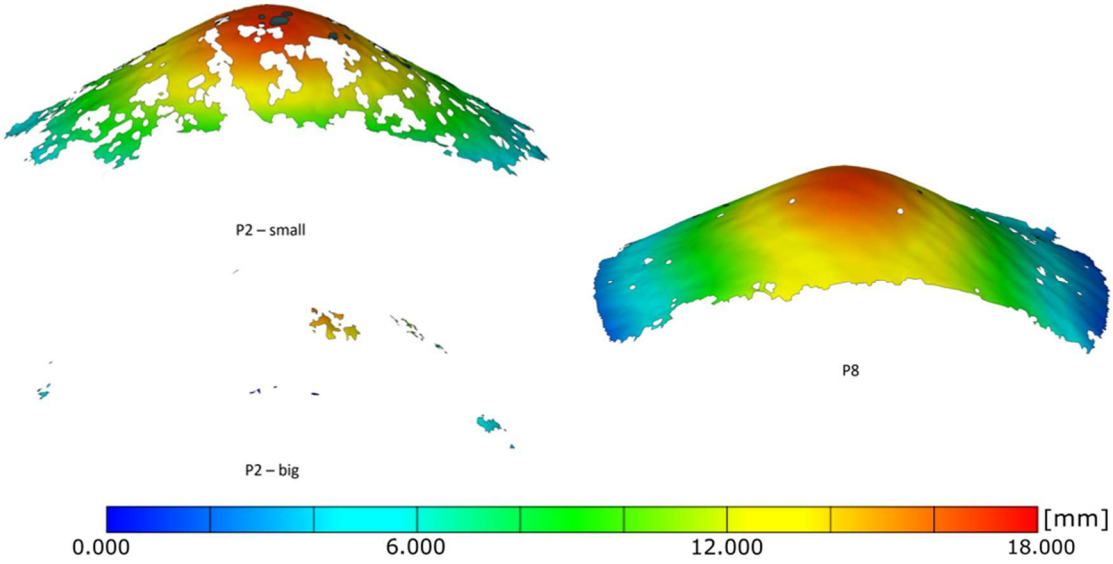

Fig. 9. Three results of DIC Measurements: On the left, in the case of the P2 paint, and on the right, in the case of the P8 paint.

4. Conclusions

The following conclusions can be drawn from the summary of the research results. The tests clearly confirmed that the reliability of DIC measurements performed on natural skin tissues depends significantly on the storage and preparation of the samples, as well as the choice of dyeing method. Storage tests have shown that porcine skin samples should be stored frozen for no longer than one week, and that samples stored in a refrigerator should be measured within 24 hours at the latest. It is also recommended that thawed and prepared samples stored in the open air be used within 4 hours to prevent the surface from hardening.

The results of the dye tests showed that cosmetic dyes behave very differently from industrial dyes. Although most dyes did not dry completely on the skin surface, this property proved to be advantageous in mediating shape change. The fast drying and even coverage of the henna-based dye (P2) was a significant advantage, while dyes P6 and P8 showed good coverage and adhesion in the dyeing qualification tests. DIC measurements confirmed that even paints that did not dry completely were able to reproduce the reference displacements with an accuracy of less than 2%. Of the paints, P6 and P8 provided the best quality and most saturated point cloud, while in the case of P2 and P3, the dispersion of the point clouds may limit the interpretation of the total surface deformation.

Overall, the research has shown that sample handling and dye selection are crucial for the reliability of DIC tests. The results provide a methodological framework that will guide future measurements on skin tissue and contribute to more accurate, detailed and reproducible deformation maps.

Looking forward, this research offers several promising avenues for development. One possibility is the incorporation of artificial intelligence and machine learning methods [37–39], which could enable the prediction of the behavior of paints and skins considering different types and different circumstances. Decision-making approaches, such as fuzzy logic [40–42], may also prove valuable for evaluating measurement results. AI-driven optimization tools, such as neural networks and genetic algorithms [43–45], as well as early-stage cost-reduction strategies [46], can further enhance process efficiency. Decision-making [47, 48], optimization [49, 50], as well as traditional mathematical statistics [51–54] can also be essential for future research directions.

Author Contributions

S. SZALAI., V. NEMES, B.F. SZÍVÓS, M.G. LÉGRÁDI, and S. FISCHER planned the conceptualization, designed the methodology, developed the software, and carried out the validation, formal analysis, and investigation. They also contributed to the resources, data curation, and original draft preparation. The writing—review and editing, as well as visualization, were performed by S. SZALAI., V. NEMES, B.F. SZÍVÓS, M.G. LÉGRÁDI, and S. FISCHER S. SZALAI. and S. FISCHER supervised the work, administered the project, and acquired the 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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