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Keynote Speech on Skin Biomechanics: An Experimental-Numerical Integration

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Abstract**—Skin, the largest organ of the human body, is essentially a vital organ, which apart from offering outward appearance to a person, provides protection. Owing to the intricate nature of skin, measuring and quantifying its mechanical behaviour as well as its properties is indeed a challenge. A number of studies have been carried out to enhance ones understanding of skin's behaviour and properties by establishing the numerical value of skin parameters based on hyperelastic models. This paper reviews recent experimental techniques employed in the study of skin mechanics with regard to human and bovine skin. This work also explores the phenomenological experimental-numerical fusion technique, which results to tangible quantification of biomechanical properties of skin.**

Index Terms**—skin biomechanics, *in vivo*, *in vitro*, motion capture, tensile test, FE simulation, Matlab, hyperelastic models**

I. INTRODUCTION

As skin articulates the apparent appearance of a person, it signifies societal importance. Nevertheless, the indispensable scale of its basic functions, are only often appreciated upon severe ailment or injuries [1]. Hitherto, amidst the most sophisticated physical injuries to be evaluated and overseen are unarguably burn injuries as it affects not only the physical condition of survivors but also more importantly their psychological state.

A number of skin substitute options are presently available, namely autografts, allografts, xenografts as well as engineered synthetic skins. Although autografts are deemed to be the most preferred option in surgical reconstruction procedures, it is often not feasible in clinical practice specifically in cases where large total surface area of the body is burnt. This scenario is generally due to the physiological condition of the patient, which impedes the harvesting of skin as well as the inadequate amount of skin for autografting available at the time of burn removal [2].

Owing to that fact, other skin substitute options are increasingly sought after in facilitating wound healing and replacement in several different clinical settings [3]. Nonetheless, these skin substitutes are not free from issues such as graft rejection, availability, ethical and cultural ramifications as well as the risk of disease transfer [4]. Skin substitutes, ideally should be able to replace all of the structures and functions of native skin. However, not all skin substitutes can entirely duplicate the intricacy of the human skin.

Due to the complex nature of skin, great effort has been given continuously by academia in an attempt to understand the behaviour of skin in order to facilitate the study of skin substitutes. From an engineering standpoint, the mechanical behaviour of skin and its properties is of wide interest and importance, as it is still not well defined or understood. This paper reviews recent experimental techniques and numerical works explored in quantifying skin mechanical properties as well as establishing numerical value of skin parameters based on hyperelastic models for both humans and animals alike.

II. SKIN STRUCTURE AND ITS MECHANICAL PROPERTIES

As skin represents relatively one tenth of the body mass, it is considered to be the largest organ in a body [5]. It wraps the body with its organised thin and complex membrane. Its structure may be divided into three distinct layers viz. epidermis, dermis and hypodermis as illustrated in Fig. 1. The skin acts as a mechanical impact cushion apart from acting as a barrier shielding against the engagement or entry of plausible harmful microorganism from the environment [6].

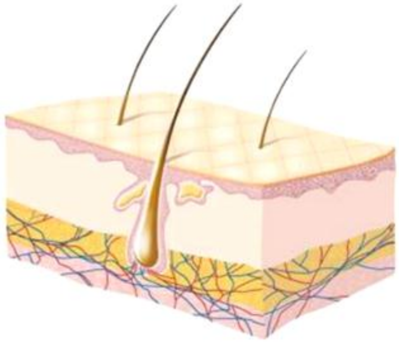

Figure 1. A simplistic schematic diagram of the human skin [6].

In order to facilitate body motion, the skin must be adequately flexible to allow a significant amount of deformations whilst preserving its ability to return to its initial state, in other words elastic. Other notable traits of skin are its toughness against resisting tear as well as piercing. Due to the complex nature of skin, it exhibits intricate mechanical properties such as nonlinear [7],

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viscoelastic [8], anisotropic [9] as well as hyperelastic [10] characteristics.

III. CONSTITUTIVE MODELS

Attempts have been made by researches [11], [12] to model skin by employing viscoelastic constitutive models over the conventional linear elastic models as it does not describe the skin model accurately. Nevertheless, the researches often adapt hyperelasticity in modelling skin, as it appears to be able to adequately describe skin behaviour [13]. Amongst the notable hyperelastic constitutive models used in skin research are:

A. Odgen Constitutive Model

The Ogden model, introduced in 1972 is a hyperelastic model that may be used in predicting the nonlinear behaviour of elastomeric like materials such as skin. The model’s strain energy density function may be written as [14]:

$$W = \sum_{i=1}^{N} \frac{\mu_i}{\alpha_i}(\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3) \qquad (1)$$

where λ_i is the principal stretch ratio, whilst μ_i and α_i are the empirically determined material parameters.

B. Mooney-Rivlin Constitutive Model

This hyperelastic model was introduced by Melvin Mooney and Ronald Rivlin. Its strain density function, W is a linear combination of two invariants of the left Cauchy-Green deformation tensor, B [15]. Equation (2) demonstrates this relationship:

$$W = C_1(\bar{I}_1 - 3) + C_2(\bar{I}_2 - 3) \qquad (2)$$

where C_i are the material constants, whilst $\bar{I}_1$ and $\bar{I}_2$ are the first and second invariant of the deviatoric component of the left Cauchy-Green deformation tensor, respectively.

C. Neo-Hookean Constitutive Model

This hyperelastic model is deemed to be one of the simplest models and found to be similar to Hooke’s law. For a given material the relationship between applied stress and strain is linear initially, however it changes to nonlinear at a certain point in the stress-strain curve. The Neo-Hookean model may be expressed as [16]:

$$W = C_1(\bar{I}_1 - 3) \qquad (3)$$

where C_1 is a material constants, whilst stretch ratio, whilst $\bar{I}_1$ is the first of the deviatoric component of the left Cauchy-Green deformation tensor.

IV. EXPERIMENTAL METHODS

Experimental techniques have been the main approach in investigating as well as providing a better understanding on the behaviour of skin. These techniques, have however, evolved from a merely simple basic laboratory testing into the employment of far more advanced sophisticated equipment owing to the advancement of technology, which includes non-invasive, *in vivo* techniques [17].

In determining skin elastic constants, the common methods used to characterise skin properties are suction [18], torsion [19] tensile [20], and indentation tests [21]. Strain is also an important parameter in the study of skin biomechanics, especially the stretch ratio, λ which is derived from the available strain data [22]. Amongst the techniques used to quantify strain are confocal microscopy and digital image correlation (DIC) [23]. The ensuing subsections will discuss in great detail experimental techniques applied in recent studies.

A. In Vivo

A novel experimental technique was developed to measure full-field deformation of human skin in vivo [17]. The initial concept was brought into inception by the authors, with its preliminary results were presented at the distinguished IMeche Medicine and Health Division Meeting in 2009 [24]. The technique generated accurate and reliable data that may be employed in studying the mechanical properties of skin. This unique technique employed a small-scale 3D motion capture system (Qualisys Proflex-MCU1000) with a focal length lens of 50mm. The camera is calibrated prior to its use to ensure its precision, this was achieved by means of static calibration with a diamond shape markers with a dimension of 3mm×2 mm as depicted in Fig. 2.

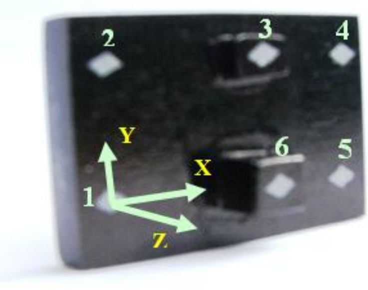

Figure 2. Calibration frame

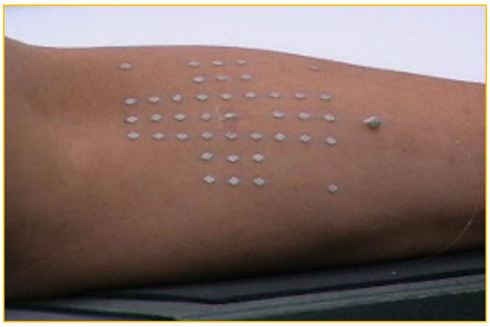

Figure 3. Markers attached on a volunteer

Five healthy volunteers aged between 23 to 42 years old (mean age of 28 years) with no signs irregularity at the area intended for testing were enlisted [17]. The volunteers provided informed consent with ethical approval from the Cardiff School of Engineering

Research Committee. The forearm length, size and the area of skin to be tested were measured. Important markings such as field of view, marker positions and the load direction were established as depicted in Fig. 3. The markers were attached and a load was applied at the centre of the marker array by pulling a fine nylon wire with a corresponding load of 1.5N in three directions, namely along the x-, y and 45°-direction, respectively to instigate skin deformation. The tests were repeated thrice for each loading condition.

The marker trajectories were tracked using the Qualisys Tracking Manager (QTM 2008, v2.0) software. The interface of the system is shown in Fig. 4, where the system is able to synchronise the outputs of motion captured and load applied.

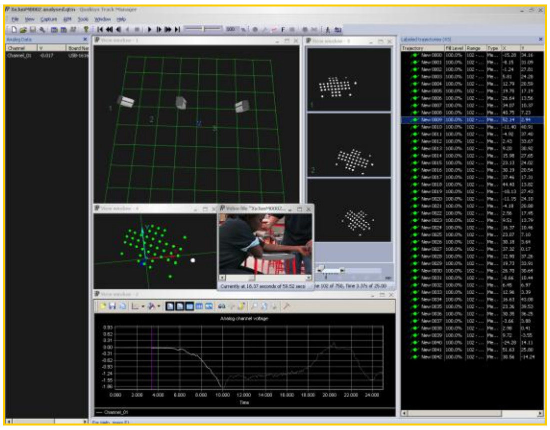

Figure 4. System interface

A similar experimental setup (Fig. 5) was employed by the aforementioned authors in extending their work in determining skin strain distribution instead of only skin deformation achieved earlier [25]. The study successfully determined the corresponding strain distribution through the integration of numerical approach. Instead of five volunteers, in this work, they recruited three whilst adhering to the ethical approval regulated by the statutory board.

The numerical method applied in achieving the strain distribution will be described in the subsequent sections of this paper.

Figure 5. Motion capture system setup

A more recent study that employs the exact same technique was conducted in order to study the effect of skin pre-stretch in quantifying skin properties [26]. Through the experimental results integrated with finite element simulations, the importance of considering skin pre-stretch in understanding further the underlying principles behind the mechanical behaviour of skin was successfully demonstrated. The experimental results obtained in the aforementioned studies will be employed in the subsequent numerical section.

B. In Vitro

In vitro route is often conducted by researchers, prior to any *in vivo* experimental procedure in order to ensure safety and reduced risk towards human subjects. Studies have been performed in identifying the mechanical parameters of animal skin such as murine, leonine, porcine and recently this includes identification of bovine skin as well. In order to quantify the biomechanical properties of bovine skin, uniaxial tension tests were conducted [27].

The study begins with sample preparation, in which the samples were prepared from a fresh slaughtered male bovine of the age of two years. The size and dimension of the skin samples are in accordance to International ASTM (D2209-00), which is a standard testing method in examining tensile strength of leather. Fig. 6 depicts the overall dimension of I-shape skin prepared with 171mm of length and 31.8mm of width.

Figure 6. Samples of I-Shape skin [27].

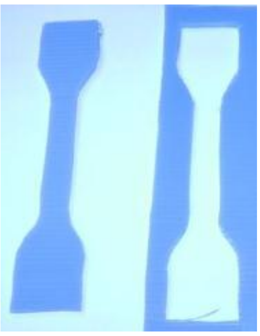

Figure 7. Template used in preparing the samples [27].

To ensure the repeatability and reproducibility of the experiment, a plastic board template (Fig. 7) was fabricated. The tensile test was performed using Instron Mechanical test machine (Instron, Dynatup 9250) at the Strength of Materials laboratory, Faculty of Mechanical Engineering UiTM Shah Alam, Selangor. The test was performed by applying load of 240N at the speed of 254± 50mm/min.

The samples were clamped with knurled jigs at both ends and were tightened accordingly to avoid slip without damaging the samples. Few samples were rejected/disposed due to slip faulty event. Only results from samples which underwent maximum loading were used. The mechanical properties such as tensile stress, elongation, strain were obtained and the derivative parameters were determined from stretch-strain formulation. The results obtained from this study were employed in numerical investigation as well as unified experimental-numerical investigations that will be discussed in the ensuing sections.

V. EXPERIMENTAL-NUMERICAL INTEGRATION

Initial works in developing computational models for skin dated back since the 1970's where human skin was modelled as a hyperelastic material as well as an elastic membrane without taking into consideration the effects of viscoelasticity. Mathematical approach was the main avenue due to the primitive computational tools existed during that period. The advancement of technology has made any attempt to simulate and animate skin behaviour possible by the employment of commercial finite element (FE) package software readily available. Attempts have been made in analysing and simulating human tissue deformation by means of ANSYS, wound closure via SYSTUS, and skin suction tests utilising MSC. MARC and ABAQUS have been used to simulate cupping process. However, it is worth mentioning that most researchers' often use the available data from experiments only to perform FE simulations without suggesting skin properties, especially the hyperelasticity property. Recent attempts hereof will be discussed with respect to human skin as well as bovine skin.

A. Human Skin

Manan *et al.* employed 2D finite element modelling in determining hyperelastic parameters of the human skin [28]. The experimental works were conducted at the Cardiff University Structural Performance (CUSP) Laboratory, Cardiff University, UK by employing the *in vivo* technique described earlier and generally, the outputs are shown in Fig. 8. The idea is to conduct a FE simulation and analysis by replicating the actual experimental set-up. Thus, the deformation data as well as other related information were used to develop the FE model (Fig. 9).

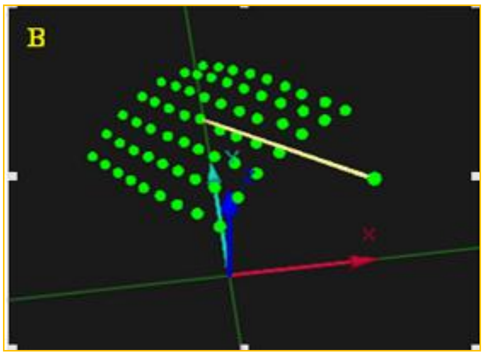

Figure 8. (A) A sample marker configuration placed on subjects' forearm. (B) The tracked markers.

A methodical parametric study was conducted through generating a series of FE models that varies in terms of material parameters, elements types and mesh sizes. The models were then evaluated iteratively and improved to match the experimental results. The material parameters that yield the results which are in good agreement (minimum error) with the experimental work are established as the estimated value of the mechanical properties of skin. This iterative method is also known as inverse-FEA (i-FEA).

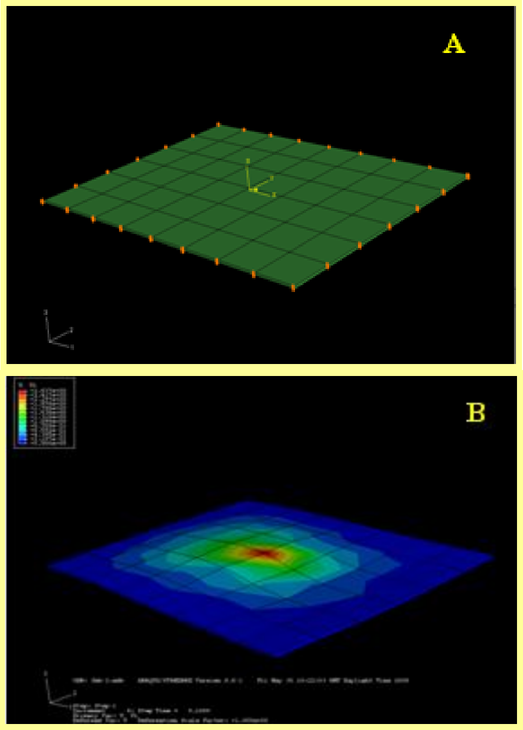

Figure 9. (A) A sample FE model representing skin. (B) The simulated deformation replicating physical tests

In this study, ANSYS was employed to model the skin of Subject 1 (0.75N) as a thin plate. A 2D plane stress quad elements (hyperelastic, 4 noded-element, PLANE 182) as shown in Fig. 8B was used to mesh the model. Fig. 9A also illustrates the load and boundary conditions which were applied as to mimic the experiment set up. 0.75N concentrated load was applied at the centre of the marker set (mimics the point load during tests) in the parallel direction to the midline markers (crease-to-crease of the ventral forearm). Based on the data extracted directly during experiments (from the measured displacements at the boundaries of the test area [17]), the boundary conditions were applied as the prescribed displacements. The actual measured displacements are fed into the Corresponding nodes to ensure that boundaries of the thin plate model are displaced according to the shape of the deformed human skin *in vivo*.

In this work, the materials property selected was nonlinear hyperelasticity, albeit the experimental results indicate that skin behaves viscoelastically, nonlinearly, hyperelastically and anisotropically. Nevertheless the assumption is considered valid as reported earlier [12]. The Ogden model was chosen as it has been shown to give good results, hence the Ogden's material coefficient, μ and exponent, α was investigated by varying μ from 10 to 110 for a constant value of 26Pa for α. A further investigation was carried out by varying α from 10 to 60Pa whilst retaining μ as a constant at μ=10. The results were then compared with the experimental results to determine the best match curve.

An extension to the aforementioned work was conducted by Mahmud et al. by means of commercial FE package, ABAQUS [29]. The exact same approach and assumptions were employed in their study. However, the experimental results vary as the point load applied in this series of tests was 0.7N. The α value was varied from 10 to 120 whilst maintaining μ at 10Pa as an initial study. μ was then increased to 15 and 20Pa, to obtain a better prediction of α, quintessentially this iterative process is again i-FEA. A sensitivity test was also investigated in this study by varying mesh size and element type. Initial mesh size of 48 elements was increased to 768 elements with linear type CPS4 (with and without the effect of hourglass control) as well as CPS4R. A further investigation was also conducted by using quadratic elements, namely CPS8 and CPS8R. It is also worth to mention that this study also incorporated a preliminary investigation on effect of 3D modelling by considering the deformation in the z-direction. 3-D plane stress hybrid quadratic elements, C3D20H and C3D20HR, respectively were assigned and the skin parameters were investigated.

A further refined study on the 3D model was developed from the previous work [30]. The work utilised commercial software ANSYS v12.1. Solid Shell (3D FINITE STRAIN 190-SOLSH190) was chosen due to its ability to accommodate large deformation and high-nonlinearity which mimics skin deformation. The dimension of the block size was defined as 8×6×15mm in order to manifest the 3D effect. The value μ and α were defined as 10 and 26, respectively to simulate the material's behaviour. In executing the mesh process, the model was divided by a number of elements at different picked lines. The numbers of element division were 8, 6 and 1 for X-, Y- and Z- axes respectively. The boundary condition for the displacement was applied at nodes surrounding the model whilst the load exerted was defined as 0.7N at the centre of the model. The simulation performed was based on static analysis with large displacement control enabled to provide better converged solutions. A sensitivity test was conducted by keeping α fixed at 26 whilst varying μ from 10 to 110 and by varying α from 10 to 40Pa with an incremental step of 5Pa at a μ constant of 10Pa.

As mentioned previously, the incorporation of pre-stretch was reported in [26]. A parametric study was conducted prior to quantifying numerical values for skin mechanical properties by mean of 2D and 3D FE modelling via ABAQUS v 6.6-1. The experimental works conducted to facilitate this work was discussed earlier (in Experimental Methods). The parametric study was conducted by evaluating the equation (4):

$$\sigma_E = \frac{\mu}{(\lambda + \lambda_P)}\left((\lambda + \lambda_P)^{\alpha} - (\lambda + \lambda_P)^{-\alpha/2}\right) \qquad (4)$$

where σ_E , λ_P corresponds to engineering stress, pre-stretch term respectively, whilst the remaining symbols has its usual meanings. This study was designed to analyse the sensitivity of the parameters with respect to the solution, proving the non-uniqueness of the present solutions as well as determining several sets of parameters that produce similar solutions.

Bilinear plane stress elements (CPS4, CPS4R, CPS8 and CPS8R) were assigned for the 2D model whilst stress quadratic elements (C3D20H, A 20-node quadratic brick, hybrid, linear pressure) were assigned for the 3D model. 48 and 384 elements were discretised in the 2D and 3D model, respectively. The loading and displacement boundary conditions applied are similar as described previously. i-FEA was employed in the iterative process, where α was kept fixed at 26 whilst varying μ from 10 to 110 and by varying α from 10 to 120Pa at a μ constant of 10Pa. The deformation behaviour was investigated by varying α from 10 to 60Pa while retaining μ also at a constant value of 10Pa, prior to curve fitting process.

Hitherto, an experimental-numerical fusion approach based on FE commercial packages were discussed, and attempts by programming means were also investigated [25]. A Matlab (vR2008b) programme was written to construct Delaunay mesh and finite elements utilizing Matlab's Delaunay built in function to quantify 2D strain distribution based on the displacement data. The programme was written to read the raw QTM marker coordinates and compute the strains. Two frames were considered viz. reference and deformed. Once load is applied, the markers moved from the reference frame via sequential deformed frames. The markers were set as nodes and elements were constructed based on the reference frame by adjoining them using a Delaunay mesh. Strains were inferred from the strain-displacement matrix, [*B*] and the triangular elements of the *B*-matrix may be computed through the following equation;

$$[B] = \frac{1}{\Delta}\begin{pmatrix} y_2 - y_3 & y_3 - y_1 & y_1 - y_2 \\ x_3 - x_2 & x_1 - x_3 & x_2 - x_1 \end{pmatrix} \qquad (5)$$

$$\Delta = x_1\left(y_2 - y_3\right) + x_2\left(y_3 - y_1\right) + x_1\left(y_1 - y_2\right)$$

where (x_1,y_1), (x_2,y_2) and (x_3,y_3) are the coordinates of the corners of the triangle. The strain in a 2×2 tensor form was obtained by multiplying a matrix containing the displacements *u* and *v* of the three corners of the triangle with the *B*-matrix defined above.

$$\begin{Bmatrix} \varepsilon_{11} & \varepsilon_{12} \\ \varepsilon_{21} & \varepsilon_{22} \end{Bmatrix} = [B] \begin{Bmatrix} u_1 & v_1 \\ u_2 & v_2 \\ u_3 & v_3 \end{Bmatrix} \qquad (6)$$

A more conventional form of (6) is the Voight notation written as

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{Bmatrix} = \begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{12} + \varepsilon_{21} \end{Bmatrix} \qquad (7)$$

Strains were measured for load applied in different directions for each subject whilst the results were presented as contour colour plots using Matlab to visualize the measured axial, lateral and shear strain distributions.

B. Bovine Skin

A numerical programming was written using Matlab to quantify and determine the mechanical properties of bovine skin [27]. A parametric investigation was conducted to investigate the sensitivity of α and μ of the following equation;

$$\sigma_E = \frac{\mu}{\lambda}\left(\lambda^{\alpha} - \lambda^{-\alpha/2}\right) \qquad (8)$$

where σ_E , λ , α corresponds to engineering stress, stretch ratio and Ogden parameter term respectively. Following that, curve fitting was performed to assess the numerical results with the experimental results obtained. The results were integrated and optimised to obtain the best bovine skin biomechanical parameters. Fig. 10 illustrates this fusion process.

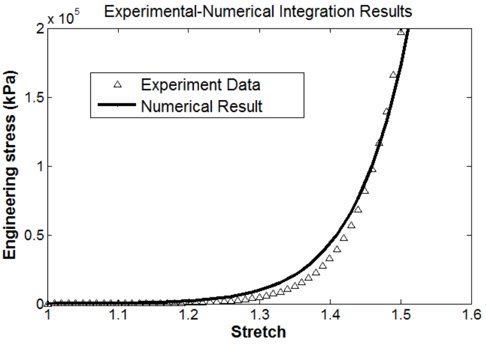

Figure 10. Experimental-numerical integration [27]

VI. DISCUSSION

In the study of skin biomechanics behaviour, it is apparent from the literature survey that there are two distinct experimental routes taken by researchers, viz. *in vivo* and *in vitro*. Owing to the advancement of technology, non-intrusive *in vivo* technique such as motion capture system was extensively described in this work. This technique is preferred as it is deemed painless towards the experimental human subjects. It is well understood that results obtained via *in vivo* method are more tangible as once skin is removed from a living body it does not exhibit its actual properties. Tensile tests are often preferred in conducting *in vitro* experimentation. However, the samples used in the investigation must be from the same animal and processed under certain controlled conditions to ensure uniformity from the results obtained.

Numerical methods have evolved over the years and with the employment of commercially available FE software in the study of skin mechanics has its immense contribution. Apart from simple 2D model to the complex 3D model, numerical programming integrated from experimental results, have been studied. Constructive heuristic iterative methods, such as the i-FEA ensure the soundness of the results attained. It is evident, that by introducing experimental-numerical fusion, quantifying tangible mechanical properties of skin is made possible.

VII. CONCLUSION

This paper highlights recent methodological advancements in the study of skin mechanical behaviour in term of experimental as well as numerical. It was shown that the phenomenological experimental-numerical fusion is deemed to produce tangible quantifiable biomechanical properties of skin. Further investigation on both human as well as bovine skin incorporating digital imaging-correlation (DIC) technique; and the employment of other hyperelastic constitutive models such as the Neo-Hookean and Mooney-Rivlin model will be reported imminently.

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