

Mechanical Behaviour of Skin: A Review

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Abstract

Objective: The mechanical behaviour or the Young's Modulus of the skin is measured as a ratio of the stress applied to the skin *in vitro* or *in vivo* over the skin deformation. The Young's Modulus of skin is an important factor to estimate the characteristics of skin, to determine the course of a disease or to follow a cosmetic application.

Methods: The mechanical behaviour of the skin is measured by changing the shape of skin by employing tensile, indentation, and suction and torsion tests.

Results: Out of all the skin's mechanical testing methods, suction tests are a common choice for skin testing, as they are easy to apply *in vivo* and consider both in-plane and normal loading conditions. Skin is found to be highly anisotropic and viscoelastic, with a range of Young's Modulus between 5 kPa and 140 MPa.

Conclusion: This paper reviews *in vivo* and *in vitro* reported values for Young's Modulus of human skin for tensile, indentation, suction and torsion mechanical testing methods.

Keywords: Young's modulus; Skin structure; Skin barrier

Introduction

Skin is composed of three layers: Epidermis, Dermis, and Hypodermis [1]. The outermost layer epidermis acts as a skin barrier. Pereira [2] considered skin to be viscoelastic, where there is a dynamic alteration in the stress-strain relationship, until a stable state is attained [3].

The stress-strain behaviour of the skin is typically explained in three phases: When a strain of up to 0.3% is applied, the elastin fibres offer low resistance to the applied strain [4]. The skin exhibits isotropic behaviour and collagen fibres remain tangled and intertwined and do not contribute to the stiffness as seen in Figure 1. Phase 1 offers a linear stress-strain relationship and a low Young's Modulus (0.1-2MPa) [5].

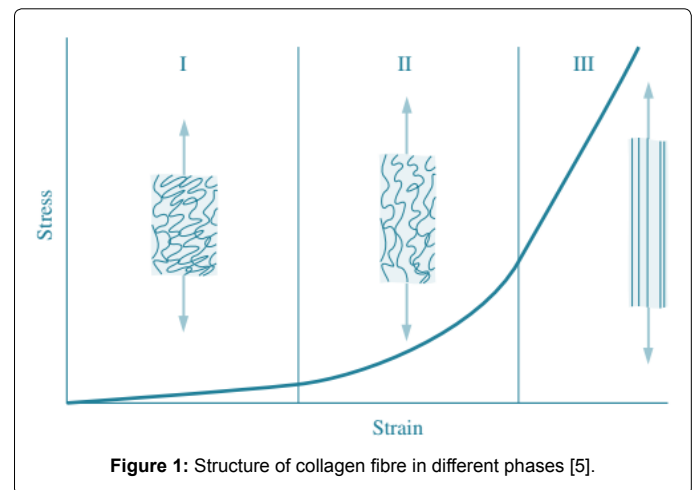
In Phase 2, the collagen fibres offer some resistance to the deformation [6] and the crimped collagen fibres begin to stretch, thus introducing non-linearity into the stress strain relationship. In the final Phase 3, for applied strain above 0.6%, the crimps begin to disappear and a linear stress-strain relationship can be observed. The collagen fibres break after the application of an ultimate tensile strain of 0.7% [5].

Young's Modulus measurements differ with many factors, including the type of test performed (*in vivo* or *in vitro*), method of testing (tensile or indentation), test velocities (in tensile testing) or depth (in indentation techniques). This paper summarises reports of the range of Young's Modulus of the human skin, considering all of the above mentioned factors. The structure of this paper can be summarised in Figure 2.

Significance of Skin's Young's Modulus

Young's Modulus of the skin is a vital parameter to estimate the characteristics of skin. One of the striking features of a healthy skin is its ability to get back to normal after being pulled. Cosmetic surgeons use a variety of topical and invasive methods to maintain the skin's elasticity to prevent ageing [7]. The mechanical testing of skin can be useful to determine the mechanical behaviour of skin in the field of dermatology, to determine the course of a disease (Scleroderma, morphea, radio dermatitis etc.) or to follow a cosmetic application. It can be used in detection of diseases in connective tissues such as mid-

dermis elastolysis [8]. The UV radiation has been found to induce skin contractions causing photo ageing which can be analysed using Young's Modulus through the stress-strain relationship [9]. Quantification of hardness, elasticity and viscosity of the skin can help estimate the skin's thickness which is a significant index for diagnosing patients with systemic sclerosis [10]. The paper summarises the many different techniques for measuring skin stiffness as a guide to interpreting results obtained in clinical practice. It also assists in the choice of techniques to be used for measuring the skin's elasticity. Knowing the Young's Modulus of skin can help in calibrating the elasticity of bio-sensors to measure skin-stretch induced motion artifacts.

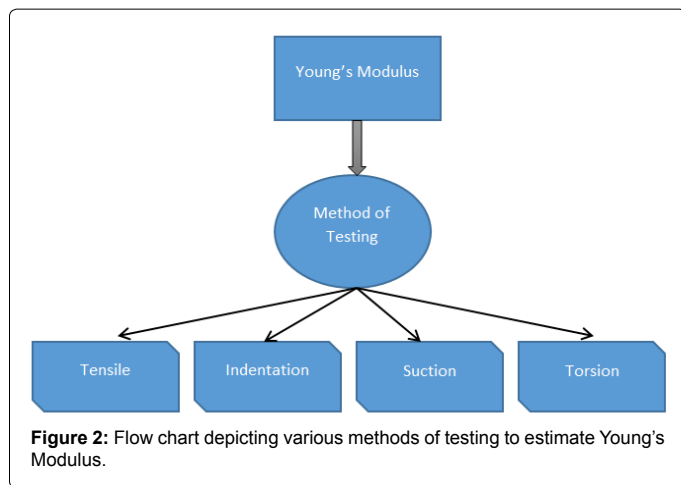


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In previous reviews, Hendriks [11] discussed several innovative techniques to determine the mechanical and structural properties of the skin such as Ultrasound, Confocal Microscopy, Optical Coherence Tomography and Nuclear Magnetic Resonance. The use of the above methods is however restricted to the measurement of skin's thickness and tomography.

This paper provides a comparative study of various mechanical testing methods used *in vivo* and *in vitro* and reviews the works of various authors, thereby covering a broad range of factors affecting the Young's Modulus of skin.

Methods: Mechanical Testing of Skin

The mechanical behaviour of the skin is measured by changing the shape of skin by employing different techniques such as stretching (tensile test), applying normal load on the skin (indentation test), elevating the skin in an aperture (suction test) and rotating the epidermis to different degrees (torsion test). All these tests have been discussed in detail in this section.

The mechanical testing of skin can be further classified into *in vivo* and *in vitro* tests. *In vitro* tests provide a simple and easy to model Stress-Strain relationship under controlled conditions with fewer confounding factors. *In vitro* tests can also be used to calculate the ultimate tensile stress and strain when the skin ruptures. However, it can be difficult to clamp samples without applying an axial load and structural integrity of the excised skin is altered particularly at the edges of the sample as it is no longer attached to the body [12]. In comparison, *in vivo* tensile measures are able to include anatomical and physiological effects on skin properties. For example, skin ageing provides a negative impact on skin's ability to perform functions like body temperature regulation and water loss prevention. Longitudinal studies of Young's Modulus values of skin must therefore be done *in vivo*.

Tensile test

Tensile testing is the most common type of test performed *ex vivo* under controlled conditions [1]. In tensile tests, the skin is stretched parallel to the plane of the skin. The load can either be uniaxial or biaxial. In early work, Manschot and Brakkee [13] performed uniaxial strain measurements on human skin (calf) and observed a non-linear relationship between stress and applied strain. The maximum and minimum values of the Young's Modulus across the tibial axis were found to be 0.32 and 4 MPa respectively and 0.3 and 20 MPa, respectively, along it. Meijer et al. [14] performed uniaxial tensile

measurements on the forearm and found the stiffness value (K_c) to be 25 MPa. The work proposed a combined numerical-experimental method based on Lanir's Skin model [15] which considers the strain-energy function to be the sum of individual strain-energy values of the tissues.

Several investigations relating to tensile testing of the skin at dynamic [16-19] and quasistatic (low level) speeds [19-21] have been reported and a summary of results is given in Table 1. Ottenio [20] performed tensile testing by clamping an *ex vivo* sample from two sides while stretching at a speed of 10 mm/min and at a maximum strain of 20%. The values of Young's Modulus were found to be dependent on the orientation of the Langer's lines.

Annaidh et al. [12] carried out uniaxial tensile tests on a human skin excised from the back at a strain rate of 0.012 s^{-1} using a Universal Tensile Test machine. The test was carried out on 7 subjects in the age group of 81-97 years and strain was evaluated using Digital Image Correlation. The mean Young's Modulus was found to be 83.33 ± 4.9 MPa.

A customised tensile device was used to measure the ultimate stress along with the longitudinal, transverse and shear strain field in an I-shaped tissue sample (taken from an 85-year old male) using Image Correlation Method [17]. The machine had been divided into an upper chamber and a lower chamber to clamp the tissue from both ends. Young's Modulus was calculated for longitudinal, transverse and shear strains by pulling down the lower chamber at a velocity of 3 ms^{-1} .

Dynamic tensile stress tests were performed by Gallagher [18] using an Instron type 8802 testing machine at different stretch velocities ($1-1.5 \text{ ms}^{-1}$). The results obtained through this study indicated maximum and minimum strain energies when the sample was placed perpendicular and at 45 degrees with respect to the Langer's lines respectively. Young's Modulus were obtained for 3 patients (aged 85, 77 and 82) for human skin excised from their backs, with stretch velocities of 1 ms^{-1} , 1.5 ms^{-1} and 2 ms^{-1} .

From Table 1, it can be inferred that the Young's Modulus measured at quasistatic speeds ($0.1-0.9 \text{ mm s}^{-1}$) varies from 4-15 MPa while for dynamic speeds ($2-30 \text{ ms}^{-1}$), it varies from 14-100 MPa. Significant fluctuations in these values have been found with different orientations like transverse and shear, however, the overall Young's Modulus increased monotonically with speed.

Indentation test

Indentation is one of the most widely used and accepted means of measurement of skin's bio-mechanical properties *in vivo*. It employs the use of an indenter which comes in to contact with and applies a perpendicular force on a small area of skin. This method characterizes

References	Skin Source	Speed	~Young's Modulus
Ankerson et al. [19]	Abdomen	Quasistatic (0.83 mms^{-1})	14.96 MPa
Annaidh et al. [16]	Not Mentioned	Dynamic (29 ms^{-1})	100 MPa
Jacquemoud et al. [17]	Forehead	Dynamic (3 ms^{-1})	14 MPa, 140 MPa and 35 MPa (for longitudinal, transverse and shear strain)
Gallagher et al. [18]	Back	Dynamic (2 ms^{-1})	83.3 MPa
Ottenio et al. [20]	Abdomen	Quasistatic Speed (0.16 mms^{-1})	4.02 ± 3.81 MPa

Table 1: Values of Young's Modulus at quasistatic and dynamic speeds using tensile testing.

skin as a monolayer by restricting the indentation amplitude to microns. However, the accurate prediction of Young's Modulus can be done only by considering the effects of underlying layers. Delalleau et al. [22] proposed a combined numerical-experimental work to estimate the skin elasticity. The skin was assumed to be a linearly elastic semi-infinite layer. Pailler-Mattie et al. [23] investigated different mechanical models to determine the effects of the underlying tissue layers and developed a two layer elastic model for mechanical analysis. The indentation method delivers Young's Modulus in the perpendicular direction without any skin pre-stressing [24,25]. The obtained values for skin's Young's Modulus vary from 4.5-8 kPa.

The value of Poisson's ratio also contributes to the obtained Young's Modulus calculations using indentation. Choi [26] performed experiments on bovine patellar articular cartilage and estimated the Young's Modulus to be 1.33-2.21 MPa for a Poisson's ratio ranging from 0.45-0.47 using single indentation test. Jia [27] in his research identified the variation of Young's Modulus with indentation depth using finite element analysis. The dynamic analysis was performed on two gel samples with different Young's moduli between 0-500 Hz using Tissue Resonator Indenter Device (TRID).

Some of the works relating to quasistatic and dynamic speeds are summarized in Table 2. Zheng and Mak [28] proposed an Ultrasound Indenter system to obtain quasistatic indentation responses of softer tissues in the lower limb. Young's Modulus was found to depend on the area, posture, gender and subject. Khaothong [29] aimed at determining the biomechanical properties of skin and muscle using an inverse finite element method combined with indentation test and found that the non-linear properties were best suited by Jamus-Green-Simpson strain energy function.

Boyer et al. [30] developed a non-invasive dynamic indentation device using very small amplitude strain (1-10 μm) and indenter penetration (100-500 μm). These small amplitudes were obtained using a piezoelectric translation stage for moving the indenter. In 2009 [31], the same authors performed tests on elastic inert materials to validate the device. In [32], an advanced device called Tonoderm® has been used to measure the Young's Modulus on human forearm. The device exerts pressure on the skin using an air compressor. The distance/depth of indentation has been measured using a laser beam passing through a Laser Displacement Sensor.

The efficiency of simple indentation measurements in thin films can be compromised by ignoring the combined contributions of the film and indenter to measured properties, as has been analysed in [33-37]. As a correction, there must be some consideration of a 'reduced Young's Modulus' which constitutes the effect of the film and the indenter. Pailler-Mattie et al. [23] analysed the effect of changing indenter penetration to a reduced Young's Modulus (E^*) of skin defined by:

$$E^* = \frac{\pi k_z}{4 \delta} \tan\left(\frac{\pi}{2} - \alpha\right) \quad (1)$$

where,

$$k_z = (dF_N/d\delta)|_{F_N=F_{Nmax}} \quad [38],$$

δ is penetration depth and α is measure of difference in 'plane strain modulus' [39].

They found the modulus to increase with increasing indenter depths. The test was carried out on different layers of tissues underlying skin (including hypodermis and dermis) and considered skin to be as a thin film over a rigid substrate (muscle).

Jia [27] measured tissue mechanical properties in terms of static stiffness and dynamic stiffness as a function of various indenter depths and found an increasing trend for both. Groves [1] conducted experiments to determine elasticity of skin at various indenter depths for spherical and cylindrical indenters, as summarized in Figure 3.

He observed that the cylindrical indenter measured a higher average value of Young's Modulus than the spherical indenter at higher indentation depths. Kuilenburg [40] also investigated the necessity of considering the geometry and size of indenters while considering the measurement of skin's elasticity. A comparative analysis of different works showed a decrease in Young's Modulus for indenter depth in microns and an increasing behaviour of elasticity for millimetre indenter penetrations. Pailler-Mattie et al. [23] carried out a study for different models accounting for skin's thickness (e) and indenter-skin contact radius (a). The apparent Young's Modulus decreased with an increasing penetration depth for $a/e < 0.5$. For the same load, the contact area of a spherical indenter is more than a cylindrical indenter; therefore, the spherical indenter exhibited a lower average value of Young's Modulus than the cylindrical indenter as observed from Figure 3.

Suction test

The mechanical properties of thin elastic membranes of materials like rubber can be determined using Diaphragm tests, where the membrane is clamped at two ends and inflated in the form of a dome (Figure 4) while the pressure of suction is controlled by a pressure controller.

Early work of Grahame [41], Alexander and Cook [42] adopted a

References	Skin Source	Speed	Young's Modulus
Khaothong [28]	Inner-forearm	Quasistatic (1 mms ⁻¹)	0.1-2.4 MPa
Zheng and Mak [29]	Tibia/Fibula	Quasistatic (0.5 – 1 mms ⁻¹)	10.4-89.4 kPa
Boyer et al. [30]	Forearm (Right)	Dynamic (1-10 μm for 10-60 Hz)	5.1-13.3 kPa
Boyer et al. [31]	Forearm (Right)	Dynamic (1-10 μm / 100-500 μm for 10-60 Hz)	13.2-33.4 kPa
Boyer et al. (Laser Displacement Method) [32]	Forearm	Dynamic (2-100 I _n min ⁻¹)	4.75-17.99 kPa

Table 2: Values of Young's Modulus at quasistatic and dynamic speeds using indentation technique.

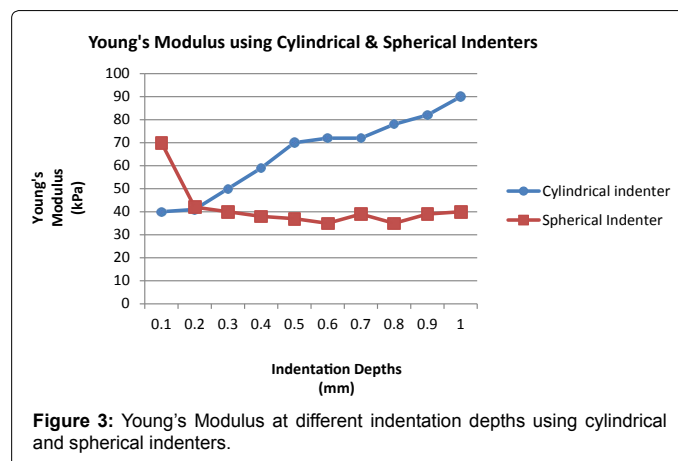


Figure 3: Young's Modulus at different indentation depths using cylindrical and spherical indenters.



Figure 4: Circular aperture of the dome used to elevate the skin in suction test.

method of suction to stratum corneum considering skin to be isotropic. Following these works, the suction method to investigate anisotropy of skin has evolved to become a common procedure for skin mechanical testing. Generally, it employs the measurement of skin elevation in a circular aperture caused due to vacuum conditions (< 500 mBar) [43] using optical systems like Dermaflex and Cutometer.

Dermaflex is a device with an aperture size of 10 mm, the cup being adhered to the skin to prevent creep. It has been used to measure skin distensibility [44] and to account for mechanical properties of dermis in [45] by measuring elasticities as a percentage of skin retraction after the stretch. The Cutometer is a suction device employing probe apertures between 2-8 mm with the application of negative pressure through a vacuum pump [46]. Barel et al. [47] determined stress-strain and strain-time curves using a Cutometer at 2 mm aperture and found a linear response within 150-500 mBar. Skin elevations of 0.1-0.6 mm were observed yielding Young's Modulus values between 130-260 kPa at different skin sites. Diridollou et al. [48] developed a suction system with ultrasound scanning-an echo rheometer capable of measuring thickness of epidermis and dermis. It operated in 3 modes at a frequency of 20 MHz and provided an axial resolution of 0.07 mm. Table 3 represents different values of Young's Modulus obtained by the suction method, measuring deformation with different aperture sizes.

Several assumptions are typically made in applying suction measurements. Hendriks ignored the mechanical contribution of epidermis in his model, instead considering that the fat layer is a major contributor for elasticity as proposed by Diridollou [49,50]. Moreover, the values of skin thickness have an effect along with the aperture size and the magnitude of negative suction pressure. Khatyr et al. [51] accounted for this aspect and compared the suction results based on three geometrical considerations of skin: thin plate, Timoshenko's geometry [52] and finite element modelling as discussed below:

Thin plate geometrical model (based on analysis of Siqueira):

$$\frac{E}{1-\mu} = \frac{pa}{2e[\text{Arc sin}\left(\frac{2au}{a^2+u^2}\right) - \frac{2au}{a^2+u^2}]} \quad (2)$$

Where,

a is radius of probe,

e is skin thickness,

p is negative pressure applied,

u is the elevation of dome,

E is Young's Modulus of material, and

μ is Poisson's ratio [53].

Timoschenko's model: It is defined by following three equations:

$$\text{Case I} \rightarrow \frac{u_o}{e} + A\left(\frac{u_o}{e}\right)^3 = B\frac{p}{E}\left(\frac{a}{e}\right)^4 \quad (3)$$

$$\text{Case II} \rightarrow \sigma_r^t = \alpha_r E \frac{u_o^2}{a^2} \quad (4)$$

$$\text{Case III} \rightarrow \sigma_r^f = \beta_r E \frac{u_o e}{a^2} \quad (5)$$

Where,

u_o is dome elevation,

σ_r^t is stress in median plane,

σ_r^f is flexion stress,

e is plate thickness,

a is radius of plate,

E is Young's Modulus,

p is pressure exerted, and

A, B, α_r and β_r are limiting parameters.

The work used Timoschenko's model, where the coefficients were optimised to fit FE modelling. The work illustrated a model for isotropic and orthotropic materials using specific initial conditions. According to the models proposed by Siqueira [53] and Timoschenko [52], the Young's Modulus exhibits an exponential increase with the increase in aperture size.

Torsion tests

Torsion measurements are carried out by applying a constant torque through a guard ring and an intermediary disc and measuring the resultant rotation of skin as seen in Figure 5.

The method is supposed to reduce the skin anisotropic effects since the underlying layers do not contribute to the readings as postulated by Escoffier et al. [54]. As the torque is applied, an immediate elastic deformation occurs followed by the occurrence of creeping viscoelastic deformation which is time dependent. The release of torque leads to immediate recovery followed by a slow recovery process which is usually not completed [55]. In torsion, the elongation is replaced by rotation and hence the measurement of elasticity becomes more complex.

Early work includes that of Sanders [56] who performed an *in vivo* analysis to determine the extensibility of skin subjected to torsion. A twist of 0.8 mN-m was applied to a disc of diameter 8.7 mm. Young's Modulus was calculated using the formula [7]

$$YM = \frac{2M(1+\mu)}{4eR^2\theta} \quad (6)$$

References	Skin Source	Deformation measurement/ Aperture Size	Young's Modulus
Diridollou [49]	Forearm	100 mBar suction/ 6 mm	130 kPa
Hendriks [11]	Forearm	350 mBar suction, Ultrasound detection/ 6 mm	56 kPa
Barel [47]	Cheek	150-500 mBar suction/ 2 mm	130-260 kPa
Liang [50]	Palm, Forearm	450 mBar/ 2 mm	25 kPa, 100 kPa

Table 3: Measurement of Young's Modulus using suction at different deformations and aperture sizes.



Figure 5: Twisting of skin for measuring elasticity in the torsion test.

where,

M is the applied torque,

e is the skin thickness,

μ is Poisson's ratio,

R is disc radius and θ is the rotation.

Agache et al. [57,58] studied the skin ageing through their experiment to determine skin stiffness through torsion. A torque of 28.6×10^{-3} N-m was applied through a disc and guard ring of 25 and 35 mm diameters respectively and rotations of 2-6° were obtained. The Young's Modulus was calculated through:

$$YM = \frac{M}{0.8\pi e r_1 r_2 \theta} \quad (7)$$

where,

M is the applied torque,

e is the skin thickness,

r_1 is the disc radius,

r_2 inner radius of guard ring and θ is the rotation in radians.

The values of Young's Modulus obtained by using torsion techniques are shown in Table 4.

Other significant works include the study of Grebenyuk and Uten'kin [59] who worked on different anatomical sites on children resulting in rotations of 7-10° at an application of a constant torque.

Discussion

Considering indentation and tensile testing, the relevance of the chosen technique mainly depends on the application. McKee et al. [60] reviewed the various indentation and tensile tests and provided a comparative insight. Tensile testing was described as a more 'direct and economical' approach. He also suggested that the value of Young's Modulus is dependent on model specific constraints such as type of test performed, controlled conditions etc. Tensile tests at a dynamic speed are generally conducted to investigate skin failure, while quasistatic speed is used to carry out conventional tests to measure the skin stiffness. In one of the works [61], dynamic speed can be used to estimate the injury levels in human skin, owing to the accurate representation of human ligament from the properties obtained at high strain rate, while quasi-static speed exhibit a linear stress-strain relationship. The values of Young's Modulus measured at quasistatic speeds are lower than those at dynamic speeds.

In general, Young's moduli found by indentation are significantly lower than those found by tensile tests, indicating that skin is highly

anisotropic when thickness and in-plane directions are considered. A contributing factor may be that Young's Modulus values are dependent on contact dimensions and range of fit. The indentation contact is very small whereas the tensile tests are macroscopic. Furthermore, in an indentation test, the Young's Modulus depends on the depth of the indenter in contact with the underlying tissues. Therefore when the depth of the indenter is small; the skin poses lower resistance from the collective effect of the underlying tissues/fibres or matrices. Conversely, these structures play a significant role in resisting tensile deformations.

In many applications *in vivo* testing would provide more relevant information than over *in vitro* testing. However, *in vivo* tests are subject to more confounding factors that are difficult to control. Conversely, *in vitro* tests typically require excised skin samples, which may be difficult to obtain. Mostly, tensile tests are performed *in vitro* by taking excised skin samples or skin patches from animals and in some cases by manufacturing skin-mimicking materials. However, some works [13,62,63] also experimented with tensile testing *in vivo* under different conditions of loading. Indentation tests are mostly performed *in vivo*, and are relatively easily applied. However the dimensions of the test site significantly affect the results. Furthermore, in applications requiring in-plane measurements, indentation is not suitable as it computes a thickness-mode response.

Torsion measurements are an accepted and reproducible means of in-plane skin elasticity analysis. However, they assume an isotropic behaviour of skin layers and a uniform deformation for the entire skin thickness. However, this consequently assumes that the applied force gradient reaches uniformly to the deeper layers of the skin. Also, since the measure of torsion is the rotational angle, it obtains, essentially, the shear modulus of the skin, which is theoretically related to the Young's Modulus.

Suction tests are a common choice for skin testing, as they are easy to apply *in vivo* and also allow for additional deformation detection through, for example, imaging ultrasound. However, this technique involves the skin undergoing both in-plane and normal loading and depends on theoretical models to determine elastic properties.

Conclusion

Skin is a highly anisotropic material. Young's Modulus in the thickness-direction typically measures between 5 to 100 kPa by indentation tests. However, measured values can depend on indenter geometry and whether quasistatic or dynamic testing is being performed. Values of between 25 kPa and 140 MPa are typical for both tensile and torsion tests. Tensile tests indicate higher Young's Modulus at higher strain rates, indicating that skin is viscoelastic. Young's Modulus measured by suction tests span 25 kPa to 260 kPa, which is between the ranges found from indentation (thickness-mode) and tensile/torsion (in-plane mode). This may be as suction tests involve both in-plane and perpendicular deformations.

Acknowledgements

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References	Skin Source	Torque/ Disc diameter/ Guard ring diameter	Young's Modulus
Sanders [56]	Forearm	0.8 mN-m/ 8.7 mm/	0.02-0.1 MPa
Agache et al. [57]	Forearm	28.6 mN-m /25 mm/ 35 mm	0.42-0.85 MPa
Escoffier et al. [54]	Forearm	2.3-10.4 mN-m /18 mm/ 24 mm	1.12 MPa

Table 4: Young's Modulus obtained using torsion using different parameters.

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