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Review Article
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An Overview of Factors Affecting the Skin's Young's Modulus

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Abstract

Skin is the outermost layer of the human body which regulates the body temperature and protects the body from abrasion and water loss. The Young's Modulus of skin is measured as a ratio of the stress applied to the skin *in vitro* or *in vivo* over the skin deformation. Skin is found to be highly anisotropic and Young's Modulus is found to be dependent on orientation with respect to Langer's lines, where highest value is seen in the parallel orientation, and can be twice the perpendicular values. Young's Modulus decreases up to three orders of magnitude with hydration. An inverse relationship between skin's thickness and Young's Modulus is observed. It can be concluded that the thickness of skin increases with age until 30 years and varies inversely with age after then. This paper summarises evidence for correlation of Young's Modulus with intramural and extraneous factors such as Langer's lines, skin's thickness, ageing and hydration.

Keywords Young's Modulus; Langer's lines; Ageing; Hydration

Introduction

Skin structure can be broadly classified into three layers: Epidermis, Dermis, and Hypodermis [1]. The epidermis is the outermost layer and acts as a skin barrier. The first two layers have a thickness of around 0.07- 0.12 mm and 1-4 mm respectively [2]. The lower region of the dermis, which is the reticular dermis, is composed of collagen and elastin fibres (0.3-3.0 μm in diameter) which deform as the fibres stretch and re-orientate [3]. Collagen is made up of protein and is cross-linked with covalent the skin samples perpendicular, parallel and at 45° to the Langer's lines [4-11]. The results have been summarised in (Figure 1).

Annaidh [12] and Gallagher [11] concluded that Young's Modulus measured at 45° and perpendicular to the Langer's lines is lower than that measured at parallel orientations. On the other hand, Ottenio [13] suggested comparable values of Young's moduli at 45° and parallel locations.

Ankersen [14] tested the mechanical properties of a synthetic chamois. He demonstrated that the corresponding strain at 45° is greater than in a direction parallel to Langer's lines. According to Catherine [15], the anisotropic effects of the skin can be minimised by applying stress parallel to the plane of the skin, thereby minimizing the contribution of the underlying layers. Liang [16] proposed a frequency dependent relationship between Langer's lines and Young's Modulus. At a frequency of 50 Hz, the Young's Modulus for perpendicular and parallel orientations were found to be comparable (100 kPa and 85 kPa) using dynamic optical coherence elastography, but at a Frequency of 600 Hz, Young's Modulus for perpendicular configuration was found to be much lower than the parallel configuration (100 kPa and 220 kPa).

Age, Gender and Skin Thickness

Human skin can be defined as a heterogeneous tissue composed of four layers viz Stratum Corneum, Epidermis, Dermis and Hypodermis. The biomechanical properties of the skin differ significantly with age. Human skin undergoes structural as well as cellular changes with age. Several studies pertaining to change in biomechanical properties of skin with ageing have been done in the past and no significant agreement was found amongst them. Young's Modulus increases with age according to Diridollou [17] and Alexander [18], but decreases with age according to Sanders [19] and Boyer [20].

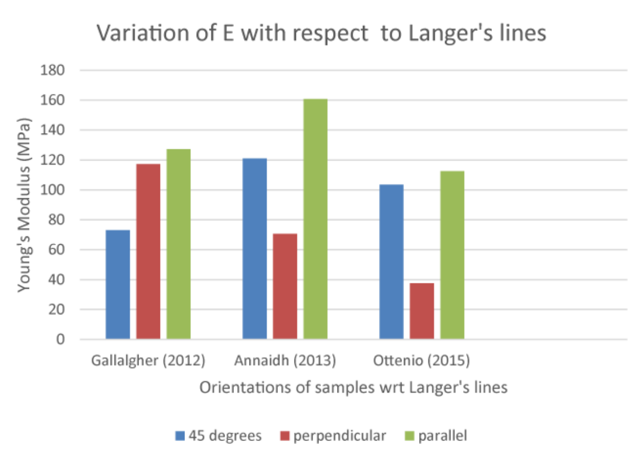

Figure 1: Variation of Young's Modulus with respect to Langer's line

Diridollou [17] conducted suction experiments on skin using an echorheometer which comprised of a cylindrical aperture filled with a coupling liquid placed normal to the skin's surface. The cylinder was integrated with a pressure control circuit used to elevate the skin and an electronic circuit to measure the skin's displacement corresponding to the first echo produced by the coupling liquid. He observed that the skin behaves differently with age for men and women and developed a mathematical equation corresponding to the change in Young's Modulus with age. The graph in Figure 2 indicates that the Young's Modulus increases after 30 and 50 years of age for both men and women. A noticeable difference in the pattern can be observed between men and women after 80 years of age. The Young's Modulus of the skin increases for men and decreases for women after 80 years. This variance in trend can be understood by considering the effect of skin's thickness with age in male and female. It was assumed that the skin's thickness increases between 10-20 years, lowering Young's Modulus values and decreases after 50 years. The increasing behaviour of Young's Modulus can be explained on the grounds of change in metabolic activities and composition of collagen with age. Catherine [15] performed some experiments using a Twistometer (Torsion Technique) and concluded that the skin's thickness and elasticity decreases notably after 65 years of age, leading to an increase in Young's Modulus. A possible explanation for this drastic change can be an increased interaction and untangling between the collagen fibres network with ageing [21].

Alexander [18] observed that Young's Modulus of the skin decreases initially up to 30 years until skin reaches a maturity level, and then begins to rise indicating an increase in stiffness. Firooz [22] concluded that Young's Modulus increases with age and found skin's elasticity to be slightly higher in female subjects than in males. However, Ishikawa [23] reported no significant correlation between skin's elasticity and sex.

Agache [24] studied the mechanical properties of skin *in vivo* by using the torsion technique. According to his experiments, the elasticity of the skin decreased after 30 years of age. The values of Young's Modulus for young and old individuals were found to be 420 KPa and 850 KPa respectively.

Hara [25] suggested that the Young's Modulus of the epidermis layer of the skin increases with age, while that of the dermis layer remains constant with age. Molak [26] performed experiments using indentation technique and found out that the Young's Modulus increased with age and remained unaltered for the indenter depths of 200 and 600 nm respectively.

In contrast, many studies found that the Young's Modulus of skin decreased with age. Boyer [20] assessed the skin's stiffness with age in 46 subjects by using a dynamic indentation method. The values of Young's Modulus for the youngest and the oldest group were found to be 10.7 KPa and 7.2 KPa respectively. A possible reason for this type of behaviour is that the skin s age, thereby lowering the Young's Modulus measured by an indenter.

Sanders [19] measured the mechanical properties of skin in males and females using the torsion method. A continuous decrease in Young's Modulus with age for men and women was observed through (Figure 2). Discontinuity and wear and tear of the collagen network with age can justify the sagging of the skin, which leads to a decline in Young's Modulus.

The anisotropic properties of the skin can be explained due the different orientation of collagen fibres in the dermis, as discussed earlier. Catherine [15] analysed the variance of thickness of skin with ageing and determined a linear regression equation for men and women, where Ep is the skin thickness in millimetres. A FIGlinear regression equation for men and women up to 30 years [15].

$$Ep = 0.7 + (8 \times 10^{-3} \times age);\ p = 0.013 \qquad Eq.\ (1)$$

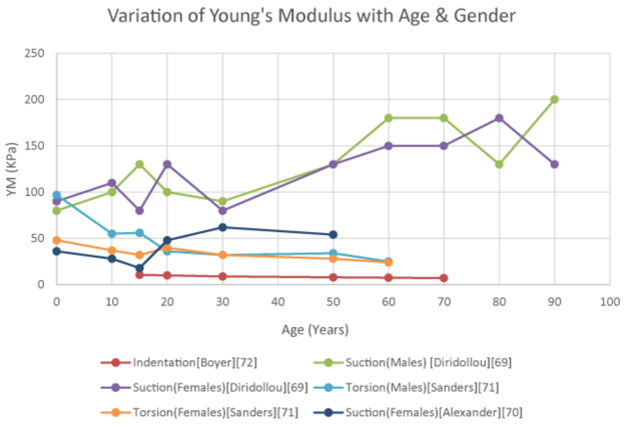

Figure 2: Variation of Young's Modulus with Age & Gender

Separate relationships were determined for men and women after 30 years:

For women:

$$Ep = 0.89 - (3 \times 10^{-3} \times age) \qquad Eq.\ (2)$$

For men:

$$Ep = 1.05 - (4 \times 10^{-3} \times age) \qquad Eq.\ (3)$$

The relation between skin's thickness and age was found to be inverse after 30 years, but men's skinwas found to be 16% thicker than women after 30 years. Diridollou [17] used an ultrasonic scanner to measure skin thickness and found the thickness of men's skin to be 5.2% greater than women. He used a mathematical model to calculate the Young's Modulus, considering various parameters such as the skin's thickness, area of the skin to be measured, initial stress and the Poison's ratio. However, the effects of Langer's lines and hydration of the skin were ignored.

Zheng [27] and Yusuke [25] found an inverse relation between skin's thickness and Young's Modulus. Zheng observed that the average value of Young's Modulus for men at different sites and different postures was 40% more than that of females.

Kuilenburg [28] modeled the contact behavior of human skin using indentation and suggested to consider the effect of all layers of skin to calculate the effective Young's Modulus, which is in contradiction with others [20]. This study [28] accounted for the dependency of Young's Modulus on various factors such as age, contact area, aperture of the indenter, depth of indentation, hydration and thickness of the skin. Also, measured Young's Modulus of the skin varied inversely with the contact size of the indenter. The effect of orientation of the collagen fibres on the Young's Modulus was not considered in this study. Young's Modulus was found to decrease with age in contrast to [15,18,24]. Moreover, the thickness and Young's Modulus evaluated in this study was different from those found using an Optical coherence Tomography (OCT) [16] and Cutometer [25]. OCT implemented interferometric techniques to estimate the optical scattering at various depths. A table comparing the Young's Modulus of different layers of skin found in various studies is shown in Table 1.

Layers	**E (Indentation) [28]**	**E (OCT) [16]**	**E(Suction) [25]**
Stratum Corneum	500 MPa	100 kPa	1.993 MPa
Epidermis	1.5 MPa	25 kPa	0.066 MPa
Dermis	8-35 x 10^{-3} MPa	75 kPa	
Hypodermis	2 x 10^{-3} MPa	8 kPa	

Table 1: Young's Modulus (E) of different skin layers using various measuring techniques

Obviously, the elasticity and viscosity of skin also depends on the site of testing. Comparing the values of Young's Modulus from different parts of pig's skin using tensile testing, Ankerson [14] found that Young's Modulus for pig's back and belly were 15 MPa and 7 MPa respectively. Similarly when Liang [16] conducted experiments orthogonal to Langer's Lines using an OCT, he came to a conclusion that the Young's Modulus for different sites viz volar forearm, dorsal forearm and palm were 101.180, 68.678 and 24.910 kPa respectively.

Ishikawa [23] performed experiments on 191 human subjects by using a new suction device and noted that there is no significant relation of skin's elasticity with sex or degree of obesity. Although, when experiments were carried out on different body sites – finger, forearm, hand and chest, then Young's Modulus on the chest was significantly lower than that of the other three sites.

Effect of Hydration

Stratum Corneum, the outermost layer of the skin, regulates water flow through the skin and acts as a barrier against the penetration of foreign substances. Many studies have shown the effect of hydration on the mechanical properties of skin. Kuilenburg [28] found out that the effective Young's Modulus of the Stratum Corneum decreased significantly with increase in hydration. On the other hand, the other layers of skin showed a minor influence of hydration on the magnitude of Young's Modulus.

According to Blank [29], Stratum Corneum receives moisture from the fluids which are present in the layers beneath it. Sweat glands become active at temperatures above 30°C. Moreover, unclothed areas tend to lose some water content due to evaporation, reducing the moisture content of Stratum Corneum to below that for the underneath layers.

Park and Baddiel [30] stated that water behaves as a plasticizer and converts the skin from a glassy state to a rubbery state. At low hydration levels, the elasticity increases due to stretching of bonds, but at higher hydration levels, the hydrogen bonds become hydrated (weak) and the sulphide bonds remain intact, thereby leading to the formation of lightly cross-linked network of collagen fibres. Wildnauer [31] reported that under controlled room temperature, the fracture strain of Stratum Corneum excised from the human upper back increased from 20% to 190% when the relative humidity was increased from 0 to 100%. Papir [32] investigated the change in mechanical properties of the Stratum Corneum in rats pertaining to alterations in hydration and temperature. It was observed that the Stratum Corneum became more elastic and ductile with increasing moisture content. Additionally, at 22°C and 77% relative humidity, a steep fall in the value of Young's Modulus was observed (Figure 3). It represents a comparison of different works showing variations in Young's Modulus with relative humidity.

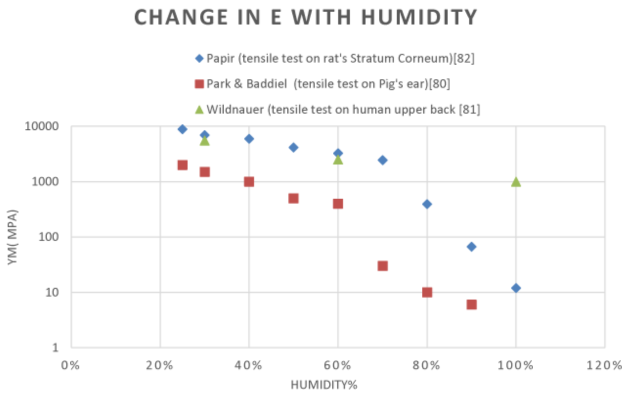

Figure 3: Change in Young's Modulus with Humidity

Uniaxial tensile tests were performed on wet and dry synthetic chamois by Ankersen [14]. High moisture content in the synthetic chamois caused a slight increase in both failure stress and strain, demonstrating the increase in elasticity on increasing the hydration on skin.

Liang [16] investigated Young's Modulus using an OCT at different frequencies for wet, dry and normal skin. The values of Young's Modulus obtained at a driving frequency of 50 Hz were the lowest for wet skin and the highest for dry skin. At larger frequencies of around 500 Hz, the wet and normal skin experienced a gain in Young's Modulus, though there was a dramatic decline in the Young's Modulus of dry skin.

Discussion

Langer's lines: In-plane anisotropy also exists, and Young's Modulus has been found to be at a maximum in directions parallel to Langer's lines. This is due to the fact that at parallel orientations, load is taken by stiffer collagen threads. However, skin Young's Modulus also changes with strain and the effect is more pronounced at higher strains.

Ageing and skin's thickness: Majority of the works suggest that the value of Young's Modulus increase with age. Many possible explanations were given for the increasing trend of Young's Modulus with age. Hall [33] suggested that there is a decrease in the ratio of chondroitine-sulfate and keratin-sulfate in dermis with age, which leads to a diminished ability of the collagen fibres to allow deformation. Another explanation given by Park and Baddiel [30] was that with age, the water content of skin decreases, therefore skin loses its rubber like properties and becomes stiffer.

Based on all the relevant works stating the dependence of Young's Modulus on thickness, it can be concluded that Young's Modulus measure is contributed by all the underlying layers such as Stratum Corneum, Epidermis, Dermis and Hypodermis. All these layers vary in thickness and therefore provide different values of Young's Modulus. Interestingly, many works have assumed a single layered model of skin, which can be acceptable in suction measurements where skin deformations are assumed to be uniform for the underlying layers as well. However, an accurate approach implies taking a two or three layered model considering the effects of the underlying tissues which can lead to estimation of an overall Young's Modulus of the skin.

The skin's thickness is found to vary with age and body site, both of which directly influence the Young's Modulus. From above, it can be concluded that the thickness of skin increases with age until 30 years and varies inversely with age after then.

Hydration: The effect of hydration has been found limited to stratum corneum as it acts as the junction for receiving the moisture content from the external environment as well as from underlying tissues. The decrease of Young's Modulus with hydration increase is quite pronounced, although the effect of fluids (other than water) on the skin is less reported. The application of electrolytic gels or other chemicals might influence skin differently.

In general, many discrepancies are found in the estimation of Young's modulus with age, hydration, skin's thickness and Langer's lines. These discrepancies can be due to the different types of tests performed such as tensile tests, indentation tests, and suction or torsion tests.

Conclusion

In-plane measurements of Young's Modulus depend on orientation with respect to Langer's lines, where highest Young's Modulus is seen in the parallel orientation, and can be twice the perpendicular values of Young's Modulus.

In addition to anisotropy, and technique-dependent variables, Young's Modulus decreases up to three orders of magnitude with hydration, and this effect appears primarily confined to the stratum corneum.

The relationship with demographic features such as age is less clear but is possibly biphasic, with increasing Young's Modulus below 30 years, and decreasing values thereafter. No consistent difference between sexes is observed. Several studies showed an inverse relation between the skin's thickness and the Young's Modulus, and skin thickness is also dependent on age, sex and body site. This suggests individual variation is much greater than age and gender effects on their own.

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