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Measurement of the mechanical properties of skin with ballistometer and suction cup

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Background: There is no consensus on the methodology for describing the mechanical properties of human skin in vivo. Current descriptions are generally method dependent.
Method: The mechanical properties of palmar skin of the hypothenar as well as dorsal and ventral forearm skin were studied in 17 healthy volunteers. Two methods were used: ballistometry [Dia-stron Torsional Ballistometer (Diastron Ltd., Andover, UK)] and suction cup [The Dermaflex machine (Cortex Technology, Hadsund, Denmark)].
Results: A moderate degree of correlation was found between the methods (r_s=0.315–0.540), while internal correlation between different measures obtained with one method was higher (r_s=0.375–0.967). The suction cup method parameters (distensibility and elasticity) correlated significantly with the ballistometry parameters (indentation, alpha, area and coefficient of restitution), while the hysteresis did not correlate to ballistometry parameters. The coefficient of variation of both methods (CV=0.02–0.35) was within the range obtained with other non-invasive methods, e.g., TEWL. Regional differences were identified with both methods, while only the suction cup method identified age-related changes.
Conclusions: The results suggest that while both methods may be useful, they describe related but not identical aspects of skin mechanics. The differences in measuring principle suggest that the suction cup method predominantly measures elasticity, while the ballistometer predominantly appears to measure stiffness. Hysteresis may be a unique measure of skin viscosity. Additional studies, however, are needed to specify the clinical significance of the various measures of skin mechanics.

Key words: skin – ballistometer – suction cup

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THE MECHANICAL properties of human skin are important to its normal functions. The objective measurement of skin mechanics is a relevant experimental (and possibly clinical) measure in the examination of human skin. The mechanical properties of skin can be used to verify sclerosis, scar tissue evolution, moisturiser effects and many other aspects of skin biology. As opposed to the measurement of, e.g., transepidermal water loss (TEWL), no consensus has been reached on the methodology of skin mechanics measurements (1). Different principles exist (i.e., static or dynamic), and a plethora of methods have been devised, such as suction chamber methods, indentometry, levarometry, wave propagation, linear distension (1). We are not aware of any publication that describes direct comparisons between the different methods. Such comparisons would enhance the validity of the observations and may improve our understanding of the different aspects of skin mechanics by identifying method-related differences.

Material and Methods

The mechanical properties of skin were measured using two different methods: the Dermaflex (suction chamber) and a commercially available ballistometer. The untreated skin of 17 healthy volunteers was examined.

The Dermaflex (Cortex Technology, Hadsund, Denmark) (6)

This is a suction cup device. Its 10-m probe (suction cup) is attached to the skin with an adhesive ring, and a vacuum applied in repeated, preset cycles. The underlying principle is that of measuring elasticity, as described for viscoelastic materials by Young's modulus (3). Three parameters were studied: *distensibility*, which reflects the elevation (mm) of the skin surface in the suction cup following the first cycle of suction; *hysteresis*, which measures the change in maximum elevation following re-

TABLE 1. *Mechanical characteristics of measured skin*

Method and mechanical characteristic	Palm	Dorsal forearm	Ventral forearm
Suction chamber method			
Distensibility (mm)	1.765±0.197*,**	2.047±0.463**	2.223±0.284*
Elasticity (%)	58.4±5.4*	61.9±11.6	67.6±7.8*
Hysteresis (mm)	0.214±0.054	0.226±0.008	0.196±0.034
Ballistometer			
Indentation (mm)	0.706±0.098**	0.864± 0.112**	0.916±0.125**
α	0.077± 0.058*	0.049±0.008	0.044±0.006*
CoR	0.792±0.025**	0.876±0.014**	0.883±0.014**
Area	73.90±9.51**	119.98±18.74**	131.21±22.61**

No significant differences were found between measurements of ventral and dorsal foream, although a trend is suggested. Significant differences: *$P<0.05$, **$P<0.001$; $n=17$ healthy volunteers; Palm: hypothenar prominence.

peated suction cycles (mm; i.e., the 'creep' phenomenon); and *elasticity*, which is measured and calculated as the degree of total retraction after the first cycle, expressed in percent. For distension of up to 3 mm, the accuracy is given as better than approximately 5% (3). The method has been used for the study of skin mechanics (4–6).

Diastron Torsional Ballistometer (Diastron Ltd., Andover, UK)

Ballistometry involves measurements of the skin surface after it has been struck by a known mass with a known force (7). The underlying principle is that of measuring material properties by studying the interaction of impacting masses and is based on Newtonian mechanics. The method was originally developed for testing homogenous hard industrial materials (e.g., rubber or metals), but has also been used in studies of the mechanical properties of the cornea. The method has been used for measurement of the mechanical properties of skin (8, 9). For ballistometry, four parameters were used: indentation, alpha, coefficient of restitution and area. *Indentation* is the peak penetration depth of the probe tip beneath the skin surface level, in mm (skin datum), and reflects softness. *Alpha* is the rate of energy damping, and large values indicate non-elastic damping materials. The *coefficient of restitution (CoR)* is the bounce height relative to the start height, and large values indicate high elasticity of the sample. *Area* describes the area between the bounce profile and the skin zero datum (i.e., the sum of the area under the curve described by the probe vs the resting level of the surface of the skin) and is therefore correlated to both softness and elasticity.

TABLE 2. *The coefficient of variation*

Method and mechanical characteristic	Palm	Dorsal forearm	Ventral forearm
Suction chamber method			
Distensibility (mm)	0.11	0.23	0.13
Elasticity (%)	0.09	0.19	0.12
Hysteresis (mm)	0.18	0.35	0.17
Ballistometer			
Indentation (mm)	0.13	0.13	0.14
α	0.13	0.17	0.13
CoR	0.03	0.02	0.02
Area	0.13	0.16	0.17

Coefficients of variation were calculated on observations in triplicate for measurements conducted on 17 persons.

Areas measured

Measurements were taken from three different regions: the palm of the hand (hypothenar prominence), and the ventral and dorsal sides of the forearms at equidistant points from the elbow joint. The regions were chosen for their clinically different mechanical properties, with the palm stiffer than the dorsal forearm and the ventral forearm. In addition, important anatomical differences exist: the palm contains loosely structured dermis and thick stratum corneum, while the two forearm sites are more uniform in skin thickness, are exposed differently to UV irradiation and, thus, are hypothetically of different mechanical properties.

No area was treated in any way or immersed in water for a minimum of 1 h prior to the measurement. All measurements were made in triplicate, and the average value was used in the following analysis. Nonparametric statistics were used for analysis.

Results

Data from the measurements and the coefficients of variation found are given in Tables 1 & 2. Systematic changes were noted in the three regions studied, with palmar skin being stiffer and less elastic than skin on the arm. Significant differences appeared in the measurements of palm, dorsal and ventral forearm for all measures except hysteresis ($P<0.001$–0.142). The correlation between the various parameters measured by the two methods are shown for all measurements (Table 3), as well as separately for palm, ventral and dorsal forearm (Tables 4–6).

Age was associated with changes in mechanical properties in a limited number of parameters. On the palm, only ballistometry showed age-related changes in the area ($r_s=0.498$, $P<0.05$), while neither forearm region showed age-related changes. Using the suction cup method age-related changes of elasticity were seen in both forearm regions (ventral: $r_s=0.570$, $P<0.05$; dorsal: $r_s=-0.526$, $P<0.05$) but not in the palm of the hand.

TABLE 3. Overall correlations (r_s) between the parameters

Mechanical characteristic	Distensibility	Elasticity	Hysteresis	Alpha	Area	CoR	Indentation
Distensibility	×	0.641 ($P<0.01$)	0.375 ($P<0.01$)	−0.540 ($P<0.01$)	0.510 ($P<0.01$)	0.474 ($P<0.01$)	0.531 ($P<0.01$)
Elasticity		×	0.375 ($P<0.01$)	−0.375 ($P<0.01$)	0.372 ($P<0.01$)	0.315 ($P<0.01$)	0.344 ($P<0.05$)
Hysteresis			×	NS	NS	NS	NS
Alpha				×	−0.957 ($P<0.01$)	−0.940 ($P<0.01$)	−0.833 ($P<0.01$)
Area					×	0.967 ($P<0.01$)	0.880 ($P<0.01$)
CoR						×	0.828 ($P<0.01$)

The correlation (r_s) between the various parameters of skin mechanics were based on a total of 51 observations in 17 persons. NS=not significant.

TABLE 4. Correlations (r_s) between mechanical characteristics of the palm (based on measurements in 17 healthy volunteers)

Mechanical characteristic	Distensibility	Elasticity	Hysteresis	Alpha	Area	CoR	Indentation
Distensibility	×	NS	NS	NS	NS	NS	NS
Elasticity		×	NS	NS	NS	NS	NS
Hysteresis			×	0.493 ($P<0.05$)	NS	NS	NS
Alpha				×	−0.992 ($P<0.1$)	−0.959 ($P<0.01$)	−0.825 ($P<0.01$)
Area					×	0.952 ($P<0.01$)	0.837 ($P<0.01$)
CoR						×	0.751 ($P<0.01$)

NS=not significant.

TABLE 5. Correlations (r_s) between mechanical characteristics of the dorsal forearm (based on measurements in 17 healthy volunteers)

Mechanical characteristic	Distensibility	Elasticity	Hysteresis	Alpha	Area	CoR	Indentation
Distensibility	×	0.671 ($P<0.01$)	0.847 ($P<0.01$)	NS	NS	NS	NS
Elasticity		×	NS	NS	NS	NS	NS
Hysteresis			×	NS	NS	NS	NS
Alpha				×	−0.734 ($P<0.01$)	−0.717 ($P<0.01$)	−0.663 ($P<0.01$)
Area					×	0.903 ($P<0.01$)	0.814 ($P<0.01$)
CoR						×	0.645 ($P<0.01$)

NS=not significant.

TABLE 6. Correlations between mechanical characteristics of the ventral forearm (based on measurements in 17 healthy volunteers)

Mechanical characteristic	Distensibility	Elasticity	Hysteresis	Alpha	Area	CoR	Indentation
Distensibility	×	0.545 ($P<0.05$)	0.675 ($P<0.01$)	NS	NS	NS	NS
Elasticity		×	NS	NS	NS	NS	NS
Hysteresis			×	NS	NS	NS	NS
Alpha				×	−0.936 ($P<0.01$)	−0.965 ($P<0.01$)	−0.737 ($P<0.01$)
Area					×	0.914 ($P<0.01$)	0.888 ($P<0.01$)
CoR						×	0.752 ($P<0.01$)

NS=not significant.

Discussion

The definition of the mechanical properties of skin is not standardised, and the clinical correlations of various measures are not well established. This study has shown that both the suction cup method and ballistometry provide reproducible data on skin mechanics. The data show only a moderate degree of correlation, suggesting they are essentially different. Underlying methodological principles in the two methods studied imply that the suction cup method is better adapted to measuring elasticity, while the ballistometer is better adapted to studying stiffness. The observations are, therefore, interpreted as suggesting that both methods describe aspects of the mechanical properties of skin, the perception of which is loosely correlated, but which appear mutually independent. Looking at the measures produced by the two different methods, it is suggested that distensibility (suction cup method) is a better single measure of skin stiffness than the other parameters and that hysteresis (suction cup method) is a unique measure of skin viscoelasticity and, therefore, only poorly related to skin stiffness. Each method generally shows good internal correlation between the various parameters measured, e.g., distensibility and hysteresis; and the overall reproducibility is similar to that described by other non-invasive measurements of e.g., laser-Doppler flow (2).

The ballistometer essentially provides a short tap on the skin, registering the subsequent oscillations and describing them in terms of frequency and amplitude. In contrast, the suction chamber method exposes the skin surface to a prolonged suction, registering the surface movements. The measurement is based on Young's modulus, and although skin is not a homogenous tissue this principle has been used by other methods and has gained some acceptance.

In addition to the different underlying principles, the area involved in the two methods may also be of importance to the observed results. The ballistometer only taps a minute area of skin, while the suction chamber affects 0.8 cm^2, which again suggests the involvement of more structures. The ratio between the volume of the different layers of the skin (e.g., epidermis vs dermis) may therefore affect the measurements. This argument has been proposed to describe the difference between suction chamber methods using different cup sizes (10).

In order to investigate the influence of the clinical perceptions of skin mechanics and tissue composition, three different anatomical areas were selected for this study. All three areas were located on the upper extremity for ease of access and comparability with earlier studies. In the palm, a significant correlation was found between hysteresis and alpha (dampening), both parameters of tissue viscosity. This is thought to underline the importance of the stratum corneum viscosity because of its anatomical preponderance in the overall structure of the skin in this region. Hysteresis has previously been associated with dermal viscosity, and the correlation with alpha, therefore, supports the view that epidermis contributes to overall skin viscosity. The suction cup method was not found to have a good internal correlation in this area, which is in agreement with a clinical impression of a more stiff tissue. In all other measurements, the two methods obtained significant internal correlations.

In addition to regional differences, age-related changes were studied. The suction cup method found expected age-related changes (i.e., loss of elasticity in forearm skin) while the ballistometer did not. It is, therefore, hypothesized that the stiffness of the skin is not a relevant parameter for studies of ageing. The age-related changes of elasticity showed a different pattern in sun-exposed dorsal skin when compared to the relatively sun-protected ventral forearm, with dorsal skin becoming less elastic while ventral skin was increasingly elastic with age. This is in agreement with previous ultrasound studies of skin ageing that found increased sonographic density of the of the dermis with increasing age (11).

The overall correlation between the two methods was moderate, although statistically significant. It is speculated that the above factors have all contributed to the limited correlation between the two methods. Both methods have, however, previously been used for the study of the mechanical properties of skin and similar results achieved in, e.g., quantification of moisturiser effects. It is, therefore, speculated that both stiffness (ballistometry results) and elasticity (suction cup method) are relevant methods.

Additional studies that correlate objective measures to observer assessment are, however, needed to specify the clinical significance of the various measures of the mechanical properties of skin.

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