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ORIGINAL CONTRIBUTION

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Age and Hydration dependence of jowl and forearm skin firmness in young and mature women

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Summary

Background: Quantitative assessment of possible linkages between skin's firmness and water content is useful for cosmetic and clinical purposes and to better understand features of advancing age.

Objectives: Our goals were to characterize age-related differential features in skin firmness in women and determine the relationship between skin firmness and indices of skin water.

Methods: Skin firmness was quantified using handheld devices that measure the force to indent skin 0.3 and 1.3 mm ($F0.3$ and $F1.3$). Skin hydration was quantified using handheld devices that measured tissue dielectric constant (TDC) at 300 MHz to skin depths of 0.5 and 2.0-2.5 mm. All parameters were measured bilaterally in the jowl area and volar forearm of 60 women grouped by age <45 years (YOUNG) and ≥45 years old (MATURE).

Results: All measured parameters were bilaterally symmetrical at jowl and forearm. Forearm and jowl indentation forces were greater in YOUNG with statistically significant declines with advancing age with regression relations most evident at shallower indentation depths ($P < .001$). Quantitative relations for arm and jowl were $F_{0.3} = 0.256 \times \text{AGE} + 32.7$ mN and $F_{0.3} = -0.07 \times \text{AGE} + 17.7$ mN. Firmness was related to TDC values only when indentation force and TDC were assessed on the arm at the shallowest skin depths, as weakly related to firmness and was observed to change with age only when measured to a depth of 0.5 mm represented by $\text{TDC5} = 0.096 \times \text{AGE} + 32.7$.

Conclusions: Experimental finding show clear differences in skin firmness between age-groups with skin hydration playing a minor role. Possible explanations and suggestions for further studies are provided.

KEYWORDS
jowl skin, skin aging, skin elasticity, skin firmness, skin water, tissue dielectric constant

1 | INTRODUCTION

Various methods are used to measure aspects of skin's mechanical properties for widely differing purposes. These include methods that indent skin statically or dynamically to measure softness,[1,2] methods that stretch skin mostly via suction methods,[3] and a variety of imaging methods including ultrasound.[4] Easy-to-use, reproducible, and valid devices have been used for rapid mobile measurements both in experimental and clinical settings[5,6] Many of these measurements depend on research type instruments, with some specially designed or some bench bound, that are not widely available or convenient for rapid mobile measurements. More recently, two handheld devices have become available that permit rapid quantitative assessment of certain aspects of the skin's mechanical properties using indentation methods.[7]

These devices indent skin to depths of 0.3 mm and 1.3 mm while automatically recording the force required for the indentation. This force then becomes a quantitative measure of skin's resistance to deformation, or firmness, and tensile functions of skin that contribute to the appearance of aged skin or firmness.[8] Therefore, a greater force is equivalent to a greater resistance by the skin, and thus a greater skin firmness. One aspect that impacts skin firmness is related to skin hydration levels that can be locally assessed via noninvasive skin tissue dielectric constant (TDC)[9] measurements. With regard to such possible skin tissue water-skin firmness linkage, it has been stated that altered texture and structure of aged skin is largely affected by hydration and age-related alterations in structural proteins.[10] This view is not without detractors,[11] and reported increases in skin hydration do not necessarily lead to improved elasticity.[12] Despite this, there is evidence that protein damage and water changes are localized in the dermis in photoaged skin.[10] For this study, we are using the MoistureMeter devices by Delfin to quantify skin hydration in the dermis of the skin as opposed to using other devices that measure the epidermis. It has also been reported that greater dermis water content is associated with increased indentation resistance,[13] and it is our initial hypothesis that skin firmness would in fact directly correlate with skin hydration measured in upper dermis and deeper via TDC measurements.

The facial skin target area of specific interest in this study was the jowl area together with the widely studied forearm skin. Structural facial changes underlying jowl and labiomandibular fold formation with advancing age have been well described[14] with various approaches aimed at improvements in jowl area reported.[15] Although several biophysical features of facial skin have been examined[16] and aspects of facial skin firmness have been assessed in young women,[7] other pertinent quantitative distinguishing features of young vs mature skin within the jowl area have not been previously reported. Thus, a major goal of this study was to determine the age dependence of skin firmness measured via indentation methods in the jowl area and to determine the relationship between skin firmness and indices of skin water as determined by local measurements of TDC at a frequency of 300 MHz.

2 | METHODS

2.1 | Subjects

A total of 60 women participated in this study after signing an institutional review board-approved informed consent. Participants were recruited from university students, staff, and other women who satisfied the entry and exclusionary criteria. Entry age requirements were from age 18 through 44 for the young group (YOUNG) and 45 years of age and above for the mature group (MATURE). Exclusionary criteria were the presence of an open wound, skin condition, makeup, or recent skin treatments on face or forearm that would interfere with skin measurements. Prior to performing the main skin measurements, each participant completed a questionnaire to determine their Fitzpatrick score.[17] This survey included questions regarding sun exposure, medications, and skin regimens. In addition, at the end of the main measurement sequence, body composition parameters (total body fat percentage (FAT%), total body water percentage (TBW%), and arm fat percentages (AF%) of dominant and nondominant arms), which also define the dominant and nondominant sides of the face, were determined using bioimpedance measurements evaluated at 50 KHz. Characteristic features of the two age-groups are summarized in Table 1, which shows that MATURE tended to be greater than YOUNG in all body composition parameters but had similar Fitzpatrick scores. The body composition measurement procedure is described subsequently.

2.2 | Initial procedures

Participants were seated in a comfortable chair where arm muscles would be at a maximal relaxed position, and bilateral target measurement sites were marked with a surgical pen. Target sites were on the face at the jowl and on the anterior forearm which was used as nonfacial control site. The jowl sites were marked bilaterally at two cm laterally and 2 cm inferiorly from the oral commissure as illustrated in Figure 1. The forearm site was located 5 cm distal to the antecubital fossa on the anterior surface in an area free of substantial hair or underlying major veins (Figure 2). Room temperature and relative humidity were recorded at the start of measurements and were (mean ± SD) 23.9 ± 1.0°C and 53.5 ± 6.1%, respectively.

2.3 | Skin firmness measurement devices

To measure skin tissue firmness, the indentation force in milliNewtons (mN) required to indent skin to 0.3 mm ($F_{0.3}$) or to 1.3 mm ($F_{1.3}$) was determined using two commercially available handheld battery-operated devices. The device with 0.3 mm indentation is the ElastiMeter and the other device for 1.3 mm indentation is the SkinFibroMeter, both made by Delfin Technologies, Kuopio Finland. In

TABLE 1 Subject demographics by age-group. Mature subjects tended to have a greater BMI and greater body fat percentage with corresponding greater arm fat percentages

Parameter	YOUNG (N = 30)	MATURE (N = 30)	*P*-value
Age (y)	27.2 ± 7.8	56.4 ± 7.6	<.0001
BMI (Kg/m^2)	24.6 ± 5.7	29.0 ± 6.4	.01
Body fat%	30.7 ± 10.6	35.1 ± 12.4	.17
Body water%	48.9 ± 11.3	41.7 ± 13.5	.04
Dom arm fat%	30.7 ± 7.33	37.1 ± 11.2	.04
Non-dom arm fat%	31.6 ± 11.1	37.4 ± 11.2	.07
Fitzgerald score	24.3 ± 5.5	22.9 ± 4.6	.30
Right-handed	23	26	
Left-handed	7	4	

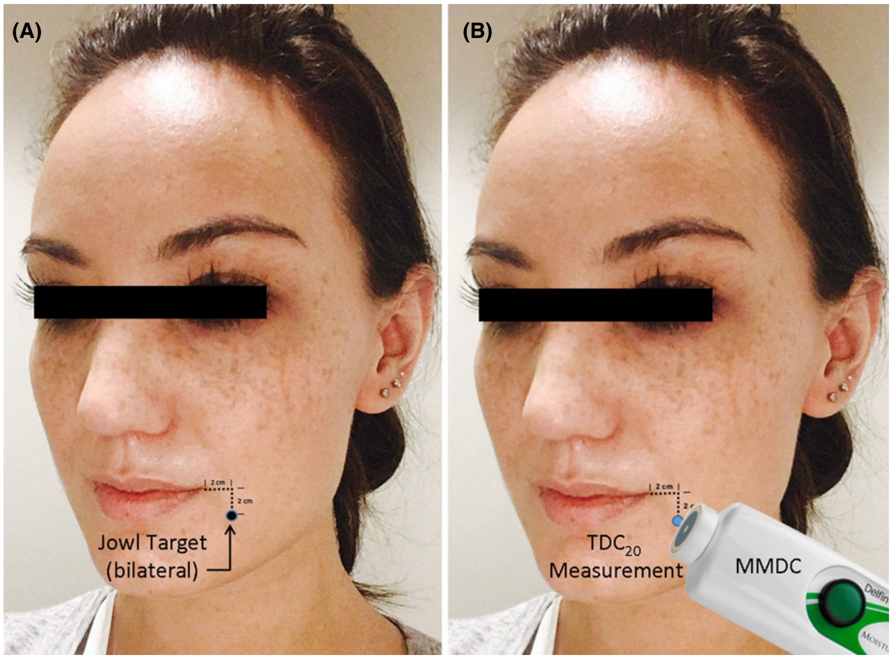

FIGURE 1 Facial measurement sites. A, Jowl sites were marked bilaterally at two cm laterally and two cm inferiorly from the oral commissure. B, tissue dielectric constant (TDC) measurements were made in triplicate by alternating measurements between left and right sides. Shown is the MMDC that measures to an effective depth of 2 mm by touching the target site with the center of the probe surface. Not shown is the 0.5 mm TDC device and the indentation force devices that are used to measure at the same targets. Also, not shown are anterior forearm sites located five cm distal to the antecubital fossa at which identical measurements are made

FIGURE 2 Forearm measurement site. Forearm sites were marked bilaterally on the anterior forearm five cm distal to the antecubital fossa. Shown is the SkinFibroMeter that measures indentation force to a depth of 1.3 mm. Not shown is the ElastiMeter that measures indentation force to a depth of 0.3 mm. Indentation forces and tissue dielectric constant (TDC) values are determined bilaterally

use, skin is lightly touched whereupon a small indenter approximately 2 mm in diameter is caused to deform skin inwardly with the resultant force recorded and displayed on a window on the front of the device. Each device is equipped with internal sensors that accept measurements only within prescribed limits of force and velocity. As a consequence, if an applied force is too large or applied too rapidly or too slowly, internal device software prompts the user to repeat the measurement until data are obtained within the set limitations of the device. A single recorded value is obtained as the average of five acceptable sequential measurements that are made rapidly in succession. The time to make these five sequential measurements at a single site is about 5 seconds. Each site was measured completely five separate times by alternating the set of five rapid measurements between right and left sides for both the jowl and the forearm sites. The average of the five completed measurements for $F_{0.3}$ and $F_{1.3}$ was determined and used as the value for each specific site.

2.4 | Tissue Dielectric Constant (TDC) measurement devices

Tissue dielectric constant, also known as relative permittivity, is the ratio of the dielectric constant of the measured tissue to that of a vacuum, and since it is a ratio, it is dimensionless. Its value is strongly dependent on the water content of the tissue being measured. TDC was measured at 300 MHz using two commercial handheld battery-operated devices that function as open-ended coaxial transmission lines.[18] Both devices are made by Delfin Technologies, Kuopio Finland, and measure TDC values to effective depths below the skin surface of about 0.5 mm (MoistureMeterEpiD, TDC_5) and about 2.0-2.5 mm (MoistureMeterD Compact, TDC_{20}). Effective depth is defined as the depth at which the excitation field within the tissue is reduced to 1/e of its surface value.[9] Both devices show values as percentage water, but the present results give the actually measured TDC values, which, for reference, is about 76 for water at 32°C. At 300 MHz, the TDC values are sensitive to both free (mobile) and bound water in the measured volume. Several reports regarding the physics and use of TDC measurements are available.[19] Both devices herein used were tested against known values of various ethanol-water concentrations to insure intrinsic accuracy with data agreeing with published values within ±2.5%. In use, the device is applied firmly but gently perpendicular to the skin for about 8-10 seconds whereupon the 300-MHz signal generated in the device is transmitted to the tissue with a portion of the incident electromagnetic wave reflected in an amount that depends on the dielectric constant of the tissue that in turn depends on the water content of the interrogated tissue volume.

2.5 | Procedures

Following marking of the target jowl and forearm sites, participants were instructed to keep their arm and facial muscles relaxed before the initiation of measurements. Skin temperature was measured with a noncontact infrared thermometer (Exergen, Model DX501-RS, Watertown MA) at the center of each target site. Thereafter, skin firmness was measured first at jowl sites and then at forearm sites using 1.3 mm depth indentation ($F_{1.3}$) and then 0.3 mm indentation ($F_{0.3}$). Following these firmness measurements, TDC values were measured first at jowl sites and then at forearm sites with the 2 mm depth measurement (TDC_{20}) done first followed by the 0.5 mm depth measurement (TDC_5). After the TDC measurements, participants removed their shoes and socks and stood on a scale for about 10 seconds while they gripped a handle electrode in each hand to measure their weight and body composition parameters via bioimpedance measurements at a frequency of 50 KHz (InnerScan Body Composition Monitor, Tanita model BC558). Parameters measured included total body fat percentage, dominant and nondominant arm fat percentage, and total body water percentage, which were determined by device proprietary algorithms based on the measured impedance values.

2.6 | Statistical analysis

Possible differences between dominant and nondominant side values for indentation force and for TDC values were evaluated using paired t tests considering the forearm and face separately. Possible differences between these parameter values between age-groups were evaluated using independent *t* tests again considering forearm and face separately. In both sets of comparisons, a *P*-value that was less than .01 was taken as evidence of a statistically significant difference. Evaluation of possible relationships between subject age and indentation force or TDC was tested using linear regression with the correlation coefficient (r) and coefficient of determination (r^2) determined.

3 | RESULTS

3.1 | Skin firmness

Table 2 summarizes skin firmness assessed by indentation forces and corresponding skin water assessed by TDC values for dominant and nondominant sides of face (jowl) and forearm for YOUNG and MATURE groups. Results show that dominant side values did not significantly differ from nondominant side values for any measured parameter on face or forearm for YOUNG or MATURE. Table 3 shows the main comparison by age-group using the average of right and left side values for indentation force and TDC values. Results show that in the jowl region, indentation forces to depths of 0.3 mm and 1.3 mm ($F_{0.3}$ and $F_{1.3}$) although tending to be

TABLE 2 Dominant and Nondominant Side Parameter Values. Data entries are mean ± SD of dominant (DOM) and nondominant (NDOM) side values and the DOM/NDOM ratio. $F_{0.3}$ and $F_{1.3}$ are indentation forces to 0.3 and 1.3 mm, respectively. TDC5 and TDC20 are tissue dielectric constants as measured to effective depths of 0.5 and 2 mm, respectively. DOM side values did not significantly differ from NDOM side values for any measured parameter on face or forearm for either YOUNG or MATURE

	YOUNG			MATURE		
	DOM	NDOM	RATIO	DOM	NDOM	RATIO
FOREARM						
$F_{0.3}$ (mN)	25.7 ± 5.6	26.1 ± 6.7	1.016 ± 0.233	18.4 ± 6.1	18.7 ± 5.5	0.998 ± 0.232
$F_{1.3}$ (mN)	53.5 ± 11.9	60.2 ± 19.2	0.950 ± 0.262	40.8 ± 16.7	43.8 ± 14.9	0.954 ± 0.304
TDC_5	35.9 ± 4.8	33.9 ± 7.3	1.020 ± 0.173	37.9 ± 4.5	38.2 ± 4.5	1.044 ± 0.029
TDC_{20}	30.9 ± 4.3	29.8 ± 4.0	1.039 ± 0.076	31.1 ± 3.9	31.5 ± 3.4	0.990 ± 0.089
TSK (°C)	32.3 ± 0.85	32.3 ± 0.91	1.000 ± 0.013	32.2 ± 0.9	32.2 ± 0.9	0.999 ± 0.015
FACE (JOWL)						
$F_{0.3}$ (mN)	15.0 ± 3.5	15.7 ± 4.2	0.978 ± 0.207	13.8 ± 2.3	14.4 ± 2.4	0.974 ± 0.209
$F_{1.3}$ (mN)	21.4 ± 5.7	22.9 ± 7.70	1.003 ± 0.321	18.8 ± 6.3	20.2 ± 7.9	1.047 ± 0.497
TDC_5	40.9 ± 6.0	40.7 ± 6.9	1.020 ± 0.173	42.5 ± 5.7	41.1 ± 4.7	1.044 ± 0.158
TDC_{20}	36.5 ± 5.7	36.1 ± 5.7	1.019 ± 0.096	38.2 ± 5.0	36.7 ± 5.1	1.044 ± 0.086
TSK (°C)	34.1 ± 0.93	33.9 ± 0.92	1.005 ± 0.018	33.7 ± 0.90	33.8 ± 0.64	0.998 ± 0.018

TABLE 3 Face and arm parameter values. Data entries are the mean ± SD of dominant and nondominant side averaged values for N = 30 per age-group. No facial (jowl) parameter differed significantly between age-groups, whereas indentation forces ($F_{0.3}$ and $F_{1.3}$) on forearm to depths of 0.3 and 1.3 mm were significantly less in the mature group. For both age-groups, tissue dielectric constant (TDC) values were greater on face vs forearm ($P < .001$) whereas forces were less on the face vs forearm ($P < .001$)

	FACE (JOWL)			FOREARM		
	YOUNG	MATURE	*P*-value	YOUNG	MATURE	*P*-value
$F_{0.3}$ (mN)	15.3 ± 3.5	14.1 ± 1.8	.09	25.9 ± 5.3	18.6 ± 5.4	<.0001
$F_{1.3}$ (mN)	22.1 ± 5.3	19.5 ± 5.2	.06	57.2 ± 12.6	42.3 ± 14.5	<.0001
TDC_5	40.8 ± 5.9*	41.8 ± 4.3*	.39	34.9 ± 5.2*	38.1 ± 4.2*	.01
TDC_{20}	36.3 ± 5.5	37.5 ± 4.8	.44	30.3 ± 4.0	31.3 ± 3.3	.31

*TDC values at 0.5 mm depth (TDC_5) were significantly greater ($P < .0001$) than at 2 mm (TDC_{20}).

greater in YOUNG were not statistically greater than for MATURE. Contrastingly, at the forearm site, both $F_{0.3}$ and $F_{1.3}$ were greater in YOUNG compared to MATURE ($P < .0001$) with $F_{0.3}$ being on average 39% greater and $F_{1.3}$ being 35% greater. Results also showed that for both age-groups, $F_{0.3}$ and $F_{1.3}$ were greater on forearm vs face ($P < .001$). For YOUNG, $F_{0.3}$ and $F_{1.3}$ were 69% and 159% greater, whereas, for MATURE, they were 31.9% and 117% greater.

3.2 | Skin TDC

With respect to TDC values, there are several findings. One relates to differences in TDC values measured to 0.5 mm (TDC_5) vs 2 mm (TDC_{20}). Results (Table 3) show that for both age-groups and both sites, TDC values are depth-dependent with values at shallower depth (TDC_5) significantly greater than deeper depth TDC_{20} ($P < .0001$). For YOUNG and MATURE, respectively, percentage differences between depth values were least at face (12.4% and 11.5%) and largest at forearm (15.2% and 21.7%).

A second result showed that for both age-groups, TDC values at both measurement depths were significantly greater on face vs forearm ($P < .001$). At a depth of 0.5 mm, percentage differences between face and forearm TDC values were larger for YOUNG vs MATURE (16.9% vs 9.2%) whereas differences were equal at 19.8% at a depth of 2 mm. A third result (Table 3) showed that, at forearm but not face, TDC_5 but not TDC_{20} was significantly greater in MATURE vs YOUNG ($P < .01$) with an average difference 9.2%.

3.3 | Age dependence

The use of regression analyses to evaluate relationships among measured parameters and age showed that the most evident relationship was that between $F_{0.3}$ and age. For arm skin, the resultant regression equation is $F_{0.3} = -0.256 \times AGE + 32.7$ mN ($r = .679$, $P < .001$, AGE in years). The corresponding equation for face is $F_{0.3} = -0.07 \times AGE + 17.7$ mN ($r = .417$, $P < .001$.

Figure 3 displays graphically these regression equations along with corresponding data for all participants. Moderate statistically significant correlations were also found between $F_{1.3}$ and age with the regression equation applicable to arm given as $F_{1.3} = -0.475 \times AGE + 69.6$ ($r = .510$, $P < .001$) and for face given as $F_{1.3} = -0.084 \times AGE + 24.3$ ($r = .258$, $P < .05$). In contrast to the decline in indentation force with age at arm and face, TDC increased slightly with advancing age only on arm and then only

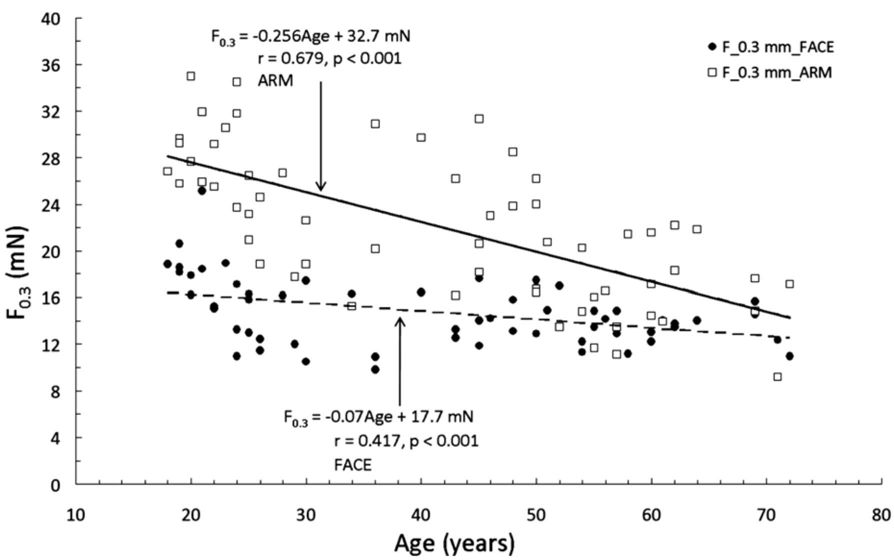

FIGURE 3 Face and Arm Indentation Forces vs Age. Right and left side average indentation force to 0.3 mm depth ($F_{0.3}$) for all participants as a function of age. Linear regressions equations are shown in the figure. There are statistically significant declines in $F_{0.3}$ with age for both the face jowl site and the anterior forearm site

when measured to a depth of 0.5 mm. The corresponding regression on age is given by $TDC_5 = 0.096 \times AGE + 32.7$, $r = .367$, $P = .004$.

3.4 | Indentation force relationship to TDC and to body composition parameters

Figure 4 shows 0.3 mm Indentation forces ($F_{0.3}$) for all arms as a function of corresponding TDC values measured to an effective depth of 0.5 mm (TDC_5). The linear regression equation shown in the figure indicates a statistically significant ($P = .012$) but minor relationship between $F_{0.3}$ and TDC_5, with only about 5% of $F_{0.3}$ variation explained by arm TDC_5. Arm $F_{1.3}$ values were not statistically related to arm TDC_{20} values. At facial jowl sites, neither $F_{0.3}$ nor $F_{1.3}$ were related to either TDC_5 or TDC_{20}. There was also no detectable correlation between any measured skin parameter and any body composition parameter.

4 | DISCUSSION

Skin indentation to assess various aspects of skin and underlying soft tissue properties is a useful technique that has been the subject of prior reports.[2,7,20] The present study was concerned with the application of this method to (i) quantitatively characterize potential age-related differential features in facial skin firmness in the jowl area and in the more commonly studied volar forearm and (ii) to determine the extent to which skin firmness in these areas is related to measures of skin hydration as determined by TDC measurements at the same skin sites.

4.1 | Skin Firmness

Skin firmness in this study is based on the force needed to indent target skin sites by 0.3 mm and 1.3 mm with the intrinsic assumption that a greater force implies greater firmness. Indentation to 0.3 mm estimates epidermal and subepidermal contributions, whereas 1.3 mm indentation additionally includes a larger proportion of dermal contribution.

One new finding demonstrates near symmetry of skin firmness between the left and right side for facial jowl and forearm skin as exemplified by near-unity dominant to nondominant side ratios as summarized in Table 2. Firmness symmetry is present in both age-groups, but absolute firmness differences are present between age-groups especially at forearm skin for which MATURE skin firmness is 26% to 28% less than in YOUNG.

The bilateral jowl and arm measurements in the present study permit a good assessment of differentials between these skin areas and show a substantially lower stiffness of jowl skin as compared to forearm. For YOUNG, jowl skin was 61% less than forearm firmness, and for MATURE, it ranged from 24% to 56% depending on indentation depth. Part of the higher value at forearm is probably linked to the presence of underlying muscle tone that is exercised more and/or not present in the jowl area. In addition, the volar forearm is a sun-protected area influenced mainly by intrinsic aging while the face is a sun-exposed area influenced mainly by factors involved in extrinsic aging such as the sun. The addition of extrinsic disturbances to the jowl area may explain for the variation in firmness between the two anatomical sites studied. The smaller differential between jowl and forearm skin for MATURE may reflect lessor forearm muscle tone due to normal physiological changes from chronological aging likely present in MATURE compared to YOUNG.

Although there is sparse prior literature describing indentation force magnitudes to depths herein used, the present levels do compare closely to prior unilateral arm and face data obtained from a group of 35 young women.[7] The present average $F_{1.3}$ values differ by less than 3% on forearm, and average $F_{0.3}$ values differ by less than 6% on face.

4.2 | Skin TDC

Tissue dielectric constant values were found to differ between depths (larger values nearer to surface) and between face and arm

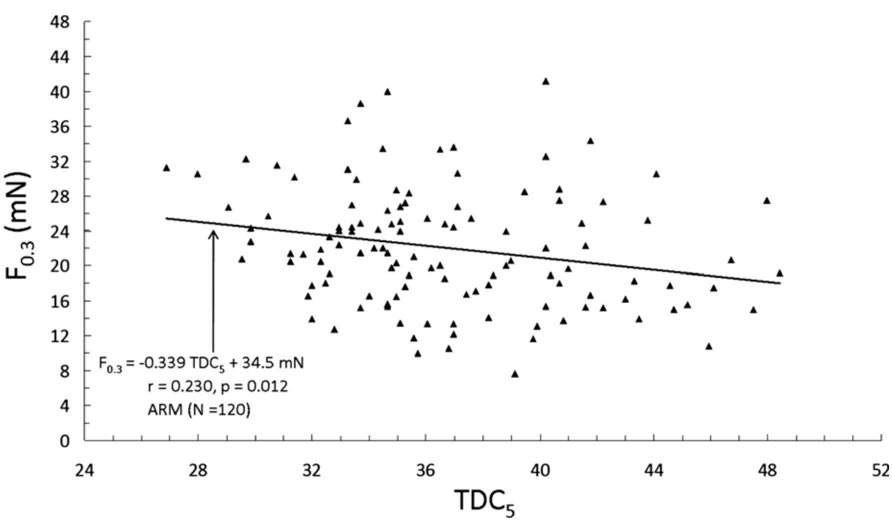

FIGURE 4 Indentation Force Relationship to tissue dielectric constant (TDC). Figure shows Indentation force to 0.3 mm depth ($F_{0.3}$) for all arms as a function of corresponding TDC measured to an effective depth of 0.5 mm (TDC_5). The linear regression equation shown indicates a statistically significant but minor relationship between $F_{0.3}$ and TDC5. Indentation force was not significantly related to TDC values at the jowl sites

(greater on face). The finding that TDC values are significantly greater if measured to a 0.5 mm compared to deeper has been observed previously for bilateral forearms,[21] but has not been previously reported for bilateral jowl area measurements. Thus, the prior forearm data are herein confirmed and the finding extended as also applying to the jowl area. A possible explanation for the depth dependence is that deeper measurements at a given site include more low-water-content fat and connective tissue compared to depths that equal to or less than 0.5 mm. A possible explanation for the higher facial TDC values as compared to forearm is the reported thicker face skin as compared to forearm.[22,23] Thicker skin favors a higher TDC value by including a greater amount of high water content dermis in the interrogated tissue volume.

4.3 | Age dependence

In an extensive review of methods for assessing skin elasticity,[24] methods with actions perpendicular to the skin included suction, traction, ballistometry, and indentation. The present findings regarding mechanical properties are based only on indentation, which is but one of the methods available. The most striking age dependency found was that between $F_{0.3}$ as measured on forearm skin that showed indentation force and hence skin firmness to decrease with increasing age. The correlation coefficient (r = .679) when squared (.461) yields the coefficient of determination that is an estimate of the amount of variation explainable on the basis of increasing age. Thus, based on the present data, about 46% of the amount of decline is explainable on the basis of age change alone. The decline in skin firmness was less dependent on advancing age when measured to a depth of 1.3 mm. At this indentation depth, only about 17% of the age variation was explainable on the basis of age alone. These indentation findings may be compared with those reported using other methods. Dynamic indentations using an indentor of 4 mm diameter to depths between 1 and 10 μm at frequencies of 10 -60 Hz were used to assess age-related forearm skin changes in persons 18 to 70 years old.[25] Indentation results were assessed in terms of a stiffness parameter K, determined as the ratio of indentation force to indentation displacement (depth) and expressed as N/m. The K parameter corresponds to the presently measured forces ($F_{0.3}$ and $F_{1.3}$) divided by corresponding penetration depths (0.3 and 1.3 mm). Using the forearm data of Table 3 for mean $F_{1.3}$ indicates K-values for YOUNG and MATURE of 44 N/m and 32.5 N/m, respectively. Such significant reductions in K were also found for the dynamic indentation data[25] with the youngest group (18-30 years) vs the oldest group (51-70) having K-values of 42.5 N/m and 28.4 N/m, respectively. Thus, the current static and the prior dynamic indentor measures seem to be in close agreement with respect to age-related directional changes and actual magnitudes of calculated stiffness parameters. It is also noteworthy that the PRESENT calculated stiffness for a penetration depth of 0.3 mm is significantly greater than for the 1.3 mm depth being 86 N/m for YOUNG and 62 N/m for MATURE. It is possible that, for smaller indentation depths, the stratum corneum stiffness plays a greater role in the overall stiffness determination. Other methods of comparing age-related skin mechanical properties using torsional extensibility[26] and suction[27] methods have also been reported, but the measured parameters are not directly comparable with indentation data.

In contrast to a firmness decline with increasing age, an increase (9%) in TDC was measured only on the arm and then only to a depth of 0.5 mm. This TDC increase with advancing age is about half of the previously reported 18% increase with older age.[28] Part of this difference may be related to the age groupings and measurement devices used. In the prior study,[28] subject age groupings were ≤age 40 vs ≥age 60 as compared to the present grouping of <age 45 vs ≥age 45 which has less of a spread between groupings but is more continuous in age with respect to regression analysis. A second difference relates to the TDC device used. The present study utilized compact devices, whereas the prior study utilized the multiprobe system. Despite the quantitative difference, both studies demonstrated an age-related increase in TDC values evident at shallow depths (0.5 mm) but not detected at deeper depths (2.0 -2.5 mm). A possible explanation for this finding resides in the fact that with aging there is a shift in the skin water status. In younger persons, skin water is largely present as bound water[29] either tightly or loosely bound to macromolecules, but this eventually shifts toward increased percentages of more mobile water with skin aging.[10] As bound water has a lower dielectric constant than mobile water,[30] such a shift would be associated with an increased TDC value reflecting greater mobile water content. The fact that the shallow depth measurement shows this effect and not the deeper depths is explainable by considering the tissue type included. TDC measurements to a depth of 0.5 mm include epidermis and part of the dermis, whereas measurements to a depth of 2 mm include dermis and some low-water-containing fat. Because the shift from bound to mobile water state occurs mainly in epidermis and dermis, a greater measurement depth reflects less of the age-related increase in mobile water and proportionately more of the low-water-content fat.

4.4 | Indentation force—TDC relationship

An additional aspect of the present work was to evaluate the relationship between skin firmness and TDC values to test the tentative hypothesis that skin firmness is inversely related to TDC as TDC is a strong indicator of skin tissue water. However, results (Figure 3) showed only a weak relationship between indentation force and TDC, with significance only for an indentation depth of 0.3 mm and TDC to a depth of 0.5 mm on arm skin. From this, we would conclude that the primary linkage between firmness and water content resides at the epidermal and upper dermal region that manifests as a relatively minor decrease in firmness with increasing hydration, at least for the population herein evaluated. The weak relationship observed may be influenced by other factors that affect skin firmness. For instance, the effects of intrinsic aging in which metabolic and reparative responses, and consequently, collagen content becomes diminished with age. Extrinsic factors include photoaging where damage from UVA and UVB rays further alter the structure of the epidermis and dermis.

4.5 | Cosmetic dermatological implications and potential uses

The present findings along with potential dermatological applications of the devices provide a useful source of information and technology to help assist with future research and clinical applications. This is especially true for undertakings designed to assess skin water content, fat content, and skin firmness in the fields of cosmetic and medical dermatology.

One example may be with respect to the use of botulinum toxin as a chemodenervation agent. The effects last about 3-4 months and possibly up to 6 months for chronic users before the recovery of the peripheral nerve terminal.[31] To help ensure safe application of the toxin, the SkinFibroMeter might be able to be utilized to further guide and confirm that the dose is within the therapeutic range if there were preinjection assessments of skin firmness. Chronic users, who have shown to have the toxin linger longer and may still have residual toxins when arriving to their follow-up visit, may benefit from such a premeasurement to avoid toxicity or adverse reactions. Because botulinum toxin weakens and paralyzes the targeted muscle area, we would expect the indentation force to be reduced postinjection.

A second possibility is related to cryolipolysis, the nonsurgical body contouring procedure that uses targeted fat cell destruction while sparing skin, nerves, vessels, and muscles.[32] Because TDC values are dependent on the amount of fat within the measurement volume, a preprocedure TDC measurement may be able to help determine treatment effectiveness via postprocedure TDC measurements that might reveal the amount of subcutaneous fat resurfacing. Accordingly, a lower TDC value would be expected at the same depth and site when compared to initial TDC measurement.

A third possible application relates to determining whether cryolipolysis impacts skin tightening in a manner similar to that reported for liposuction. The use of either the SkinFibroMeter or ElastiMeter might provide a useful way to determine whether cryolipolysis is providing the same effect but possibly from a different mechanism.

In conclusion, the findings and devices used in this study have potential utility in cosmetic and medical dermatology. The findings have helped confirm the relationship between skin firmness, age, and water content as well as opening potential new pathways in helping to assess and treat dermatological conditions. However, it should be recognized that the use of the MoistureMeterD to measure skin water changes is largely limited to changes that occur within the dermis or deeper. Because the most superficial depth the current device is able to measure is 0.5 mm, it would likely not be unable to measure effects of cosmetic formulations that mainly impact the stratum corneum with little effects on deeper skin layers. Further research must be implemented to confirm the application of these devices to the various dermatological procedures and treatments mentioned above.

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