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“Skin frequency analysis using Digital Image Correlation: a new method to evaluate dynamical movements on body skin”

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1. Introduction

The skin is a multifunctional organ, where its structure and mechanical properties reflect the body's aging process. It is made up of three main layers - the epidermis, dermis and hypodermis, and its characteristics are largely determined by the organization of the collagen and elastin fibres present in the dermis [1,2]. These fibers and their structural position give the skin elasticity and firmness.

With ageing, structural changes occur that compromise these properties, leading to fragmentation of collagen fibers, loss of elastin, reduction of dermal hydration and a decrease in skin thickness, making it more rigid, less elastic and less able to respond to external mechanical stimuli. [3-5]

The biomechanical characterization of the skin has increasingly become an object of interest, especially in the context of cosmetic products. At the moment, there are traditional methods, such as the Cutometer, which offers an analysis based on controlled suction of the skin, allowing the assessment of parameters such as firmness, elasticity and the skin's capacity for immediate recovery [6,7]. Although it is a widely used technique, this type of approach essentially measures quasi-static and punctual responses, so there is a need to look for other techniques.

Recently, several methodological alternatives have emerged that seek to understand the dynamic behavior of the skin in a way that is closer to the real conditions to which it is subjected on a daily basis. One of these approaches is the analysis of the skin's vibratory response to rapid, controlled stimuli. By applying a disturbance, such as the pressurized air jet, it is possible to induce a natural oscillation in the skin, whose dominant frequency is associated with the mechanical properties of the skin, especially its rigidity and surface mass [8,9].

Allied to this, the use of high-speed cameras and digital image correlation techniques (such as cross-correlation) allow us to track the displacement of specific points on the skin with high temporal and spatial resolution. This type of analysis provides a more complete view of the dynamic behavior of the skin, permit to identify the dominant frequencies of oscillation, but also can map how the vibration is distributed and dissipated along the surface [10,11].

Studies show that young skin tends to vibrate at lower frequencies and with greater amplitudes, while older skin behaves in the opposite way. This difference reflects the increase in skin rigidity and loss of elasticity associated with the ageing process. In this way, skin vibration frequency and amplitude can be a way of quantifying skin ageing, providing data that complements the data obtained by conventional methods, such as the Cutometer.

The objectives of this study were therefore, firstly, to develop and validate a sufficiently viable method to assess skin frequency, using a dynamic and non-invasive deformation approach. The second objective was to investigate the relationship between the dominant skin frequency and the individual's age, in order to understand how age-related structural changes, collagen degradation, elastin loss and reduced hydration affect the skin's mechanical responsiveness.

It is hoped that the results obtained in this study can contribute to a broader understanding of skin biomechanics and that they can help in new cosmetic applications aimed at skin aging.

2. Materials and Methods

After given written informed consent, forty-five women (mean age: 45.5 years) were divided into three different age groups – Young (18 to 35 years), middle-aged (36 to 55 years) and elderly (56 to 75 years). The objective is to make a comparison of the mechanical behavior of the skin in different phases of aging.

To do this, we used a standard stimulation protocol, which consisted of applying an imediate pressurized air deformation to a specific area of the face, especially in regions where there is a greater loss of firmness and elasticity over time. Thus, we were able to apply the stimulus uniformly, avoiding variations, which provides favorable reproducibility of the test. The main objective was to create a controlled deformation in the skin in a dynamic way, to understand how it vibrates under a known load.

The region of interest was filmed with a high-speed digital camera, which captured the action at 5095 frames per second. This frame rate was used to captur every detail of the slight variations in skin movement that happened quickly when the skin is hit by a brief air stimulus. High resolution is key to understanding skin wobbles, which would be virtually invisible if we used a regular camera.

In order to process the data obtained by the image acquisition system, an analysis algorithm was implemented in MATLAB. This algorithm incorporated a standardized cross-correlation algorithm in order to accurately quantify skin displacement through sequential frames. With this technique it was possible to track the movement of the skin, offering the spatial and temporal resolution necessary to capture the dynamic mechanical response. To obtain the dominant frequency and the amplitude of skin displacement associated with the oscillatory behavior of the skin, a Fast Fourier Transform (FFT) algorithm was used.

In addition to the analyses of the dominant frequency and magnitude, a 3D graph was created, where the X axis represents the time (in seconds), the Y axis corresponds to the points of the facial surface and the Z axis shows the magnitude of the displacement. This graph allows us to have a spatio-temporal perspective of how the skin surface responds dynamically to the stimulus in the region of interest.

These graphs were built based on a data matrix (Z), in which each row corresponds to a time point and each column represents a spatial location along the surface of the skin. The matrix values encode the displacement of the skin (in pixels) of each point over time, thus capturing all skin oscillations. Thus, this representation, in addition to showing the temporal evolution of the movement of the skin, also shows the way in which vibrational energy propagates through the area of interest.

To reinforce the data obtained by air stimulation and high-speed image capture, Cutometer measurements were also performed. This device is widely used in dermatological research, providing quantitative measurements of elasticity, firmness and viscoelastic recovery of the skin through the application of controlled suction to the surface of the skin. Cutometer data served as a reference to evaluate the mechanical condition of the skin in all age groups, thus reinforcing the interpretations taken from the vibrational analysis.

The parameters evaluated in the Cutometer were R0 (amplitude at the end of the suction phase), R2 (resistance to mechanical force versus recovery capacity), R5 (elastic part of the suction phase versus immediate recovery during the relaxation phase) and R7 (proportion of immediate recovery in relation to amplitude after suction).

3. Results

The results presented in Table 1, reveal a difference between the age groups. Younger individuals have a lower dominant frequency and a higher skin displacement magnitude. On the other hand, older individuals have a higher skin dominant frequency and lower magnitude. As expected, individuals in the middle-aged group present intermediate values, both for dominant frequency and displacement magnitude.

Table 1. Dominant displacement map was created in order to characterize the skin's vibratory response. In the frequency and magnitude of facial skin displacement in response to stimulation with pressurized air across three age groups (young, middle-age, and older). Frequency is expressed in hertz (Hz), and magnitude values are reported in arbitrary displacement units.

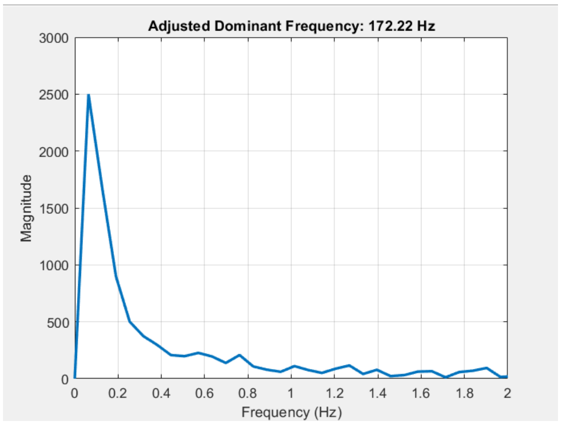
Age Ration	Dominante Frequency (Hz)	Magnitude
Young	172.22	2500
Middle-age	212.68	1910
Old	241.00	1234

In order to complement the data obtained, Cutometer measurements were performed. The results are shown in Table 2, which includes the values measured for R0, R2, R5 and R7.

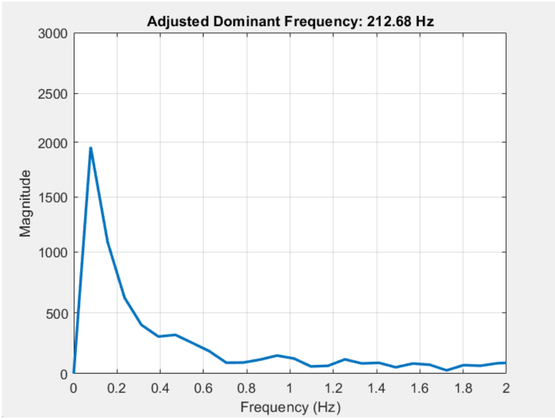
Table 2. Cutometer parameters R0, R2, R5, and R7 across age groups. R0 is expressed in millimeters (mm), while R2, R5, and R7 are dimensionless ratios.

Age Ration	R0	R2	R5	R7
Young	0.313	63.2	43.7	43.4
Middle-age	0.415	57.5	41.5	32.2
Old	0.475	41.6	37.3	30.2

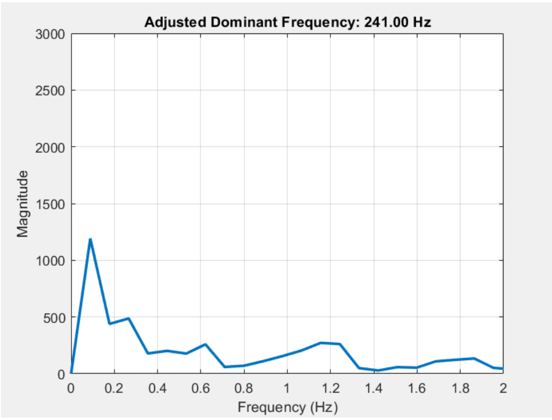
Furthermore, Figure 1 (a-c) displays the individual graphs of the subjects in each age group, where the dynamic skin response is found under the imposed stimulation. These representations allow us to observe the variability of quantitative trends in each age group in more detail.



(a)



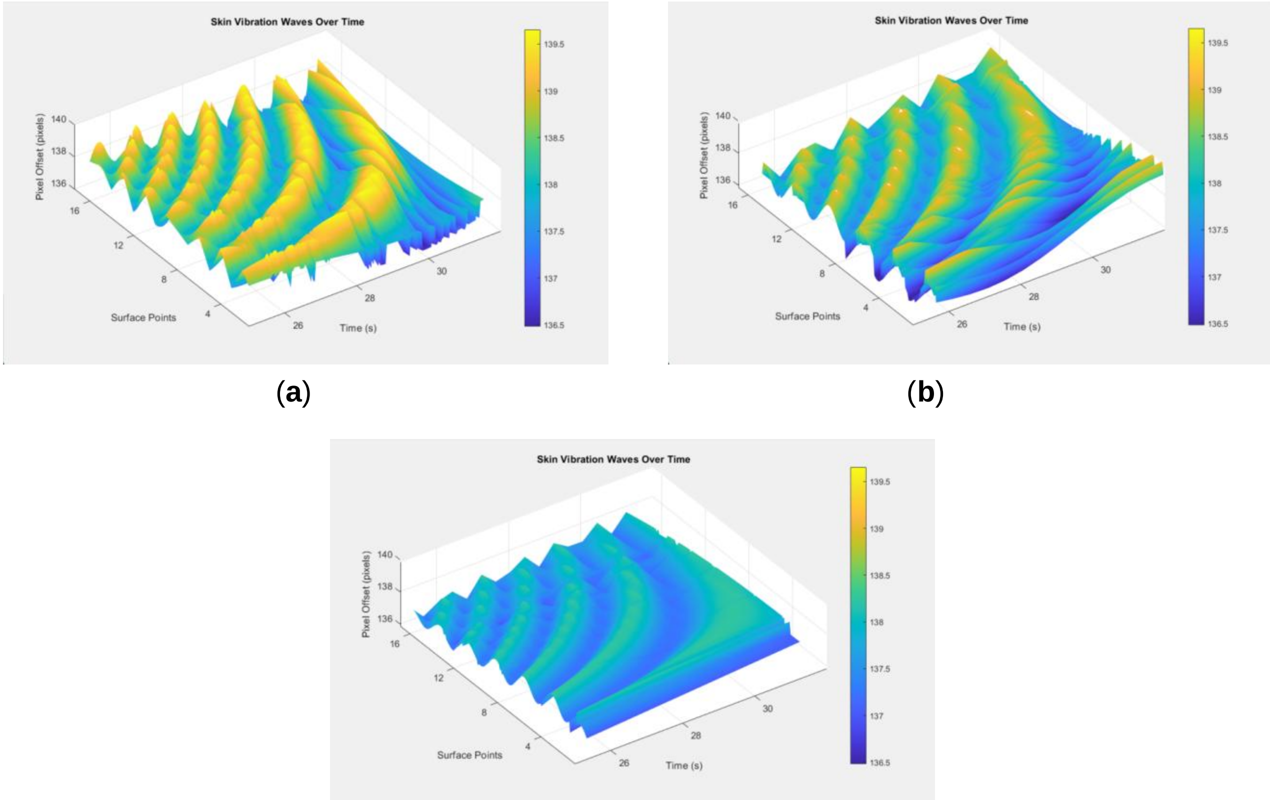
(b)



(c)

Figure 1. Displacement and frequency response of facial skin for one representative participant from each age group: (a) young, (b) middle-age, and (c) older.

In order to have a qualitative view of the biomechanical behavior of the skin under the imposed disturbance, Figure 2 (a-c) shows the 3D displacement maps of each individual. By recording spatial and temporal variations in skin displacement, these maps allow us to have a more comprehensive understanding of the skin's vibratory response across different age groups.



(**a**) (**b**)

(**c**)

Figure 2. 3D displacement maps of facial skin for representative participants from each age group: (a) young, (b) middle-age, and (c) older. Each map shows the spatial-temporal vibration pattern in response to stimulation.

4. Discussion

The present study presents and validates a new non-invasive method that allows the evaluation of the dynamic behavior of the skin, using high-speed imaging techniques and digital image visualization. By analyzing the vibrational response of the skin to a pressurized air pressure stimulus, it was possible to characterize age-related changes in skin biomechanics through dominant frequency, displacement magnitude, and oscillatory behavior. The results obtained show that these parameters change with age and that they can be used to understand skin aging.

A significant difference was observed in the results of younger individuals compared to older individuals. Younger individuals had a lower dominant frequency and a higher skin displacement magnitude. These results are in line with the physiology associated with the skin aging process, such as progressive manipulation of collagen and elastin fibers, reduction in dermal thickness, and decreased skin hydration. These changes were made to increase skin stiffness and decrease skin compliance, which may explain the increased frequency and attenuated magnitude of skin displacement in older individuals.

The greater magnitude of skin displacement observed in younger volunteers suggests that in addition to greater elasticity, there is a greater capacity for the skin to deform and recover after external mechanical loading. This is supported by the fact that younger skin exhibits more oscillatory cycles after stimulation. The increased vibrational persistence in this age group may reflect a more active biomechanical response, driven by skin resilience and more efficient energy absorption and redistribution mechanisms. These characteristics are probably linked to the fact that there is greater structural integrity, greater functional interaction of collagen and elastin and superior hydration.

The values of the middle-aged group further reinforce the notion of a biomechanical transition throughout the aging process. This change, as opposed to gross mechanical degrowth, may provide a valuable framework for assessing the onset and progression of skin aging in a quantitative manner.

Complementary data obtained via Cutometer analysis provides further confirmation of these biomechanical patterns. Although not discussed individually in the current section, the cutometric parameters (R0, R2, R5, and R7) revealed age-related variations that parallel the vibrational findings, thus reinforcing the validity of the proposed methodology. The integration of both vibrational and suction-based measurements may offer a more holistic assessment of skin mechanics, with potential applications in dermatological diagnostics and cosmetic product development.

The results obtained show the potential of the dominant frequency of the skin and the magnitude of displacement as biomechanical biomarkers that are sensitive to skin ageing, and through the interpretation of these two parameters it is possible to characterize the youthfulness of the skin, as can be seen in Table 3.

The methods presented prove to be a promising tool for future research into skin health and personalized approaches to cosmetic care.

In order to strengthen the reliability and applicability of the method developed, future studies could be carried out with a larger number of individuals.

Table 3. Characterization of skin youthfulness as a function of dominant frequency and displacement magnitude.

		Frequency	
		Low	High
Amplitude	Low		Old Skin
	High	Young skin	

5. Conclusion

Results show that people with higher firmness had a lower values of skin resonance frequency probably due to a high anchorage of the skin as observed by the results of the Cutometer. The skin frequency can drop about 28% in such cases. After a sensitivity analysis we also find that in some cases the results of the Digital Image Correlation start to be impaired even before the values of the Cutometer are off the standard body values, making this test as a more sensitive procedure for body skin changes

6. References List

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