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# *In vivo* characterization of viscoelastic properties of human skin using dynamic micro-indentation

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*Abstract*— **The human skin, the interface between the body and the outside environment, has a very complex mechanical behaviour. Knowledge of its in vivo mechanical characteristics is essential to characterize the effects of medical or cosmetic products. The aim of this work is to present a non-invasive device using dynamic indentation to quantify the viscoelatic properties of human skin in vivo. The frequency and strain amplitude are in the range of 10 to 60 Hz and 1 to 10 µm. The results on 4 subjects show that a Kelvin Voigt model describes the mechanical behaviour of in vivo human skin with dynamic indentation well. The frequency average values of stiffness and damping have also been used to compare skin properties. We found a stiffness value of 47.3 to 128.3 N/m, and damping of 0.08 to 0.121 N.s/m, corresponding to a complex modulus of 13.2 to 33.4 kPa. These results show the ability of this device to characterize viscoelastic properties of human skin.**

## I. INTRODUCTION

Human skin is the heaviest and the vastest organ of the human body. As it is the interface between the body and the outside environment, its function is vital. It is a heterogeneous and anisotropic material [1], made up of 3 layers : the epidermis, the dermis and the hypodermis [2]. Its mechanical properties are also particularly complex.

Knowledge of these properties is essential for cosmetic and clinical research. The touch of dermatologists or cosmetologists is often used to characterize skin properties. However, objective and quantitative measurements are essential to compare studies made by different people in different places. Many devices with various techniques have been used to access in vivo the mechanical properties of skin, like the suction test [3]-[4], uniaxial stretching [5], indentation [6], torsion [7] and wave propagation [8]. Due to their geometry or their design, many of these devices can not be applied on the face, which is a highly curved area. Furthermore, the mechanical properties of skin are mainly due to its very thin superficial layers, the dermis and the epidermis. It is essential to reduce the amplitude strain as much as possible to minimize the influence of underlying structure like bones or muscles.

The aim of this work is to propose a new application of dynamic indentation on human skin in vivo using a specific device. The amplitude strain and indenter penetration are very small (1-10µm and 100-500µm) to obtain the viscoelastic properties of the dermis and epidermis layers. The frequency range varies from 10 to 60 Hz.

## II. MATERIAL AND METHOD

### *A. Theory*

Although it is composed of three layers presenting various mechanical properties, the skin reacts to external stress like a mono layer material. This justifies, as a first approximation, studying the whole mechanical behaviour of the skin as if it were a homogeneous material [2].

In our case, a sine displacement u(t) [m] of angular frequency ω [rad/s] is applied to the skin surface with an indenter. The resulting force F(t) is measured. As a viscoelastic material, the indenter/skin contact can also be described by figure 1 [9].

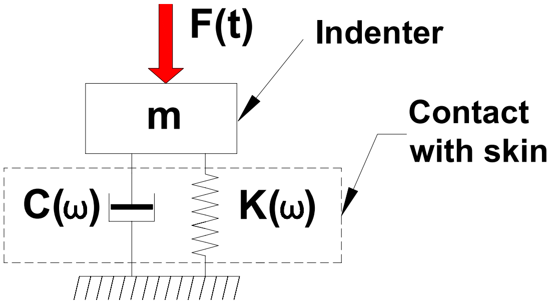

Fig. 1. Indenter/skin contact.

With m [kg] the mass of the indenter. F(t) [N] is a sinusoidal force with amplitude $f_0$ [N], given by :

$$F(t) = f_0 \sin(\omega t) \tag{1}$$

The spring of K(ω) stiffness [N/m] represents the elastic part, and the dash pot of C(ω) damping [N.s/m] represents the viscous part. The displacement u(t) has the same frequency as the force, but with phasingout φ [rad] given by:

$$u(t) = u_0 \sin(\omega t - \varphi) \tag{2}$$

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The stiffness and the damping are given by [10]:

$$K(\omega) = \left|\frac{f_0}{u_0}\right| \cos(\varphi) + m\omega^2 \tag{3}$$

$$C(\omega) = \left|\frac{f_0}{u_0}\right| \frac{\sin(\varphi)}{\omega} \tag{4}$$

The simultaneous measurement of force and displacement is sufficient to determine the viscoelastic properties of skin. If we consider an axisymmetrical indenter of radius $a$ [m] and a linear material, the complex modulus E* [MPa], with a real part E'* corresponding to elastic behaviour and an imaginary part E''* [MPa] corresponding to the viscous behaviour, is given by [10]:

$$E^* = E'^* + iE''^* \tag{5}$$

$$E'^* = \frac{K(\omega)}{2a} \tag{6}$$

$$E''^* = \frac{C(\omega)\omega}{2a} \tag{7}$$

### *B. Material*

The force and displacement of the indenter on the skin are measured by an impedance head (Brüel & Kjaer, Nærum, Denmark). This head consists of a very rigid body made of titanium, containing an accelerometer and a force sensor. Both sensors are made of piezoelectric material : they only record dynamic signals. The main advantage of using this impedance head is the coaxiality between the accelerometer and the force sensor, that minimizes the disturbing phasingout.

A driving platform is placed on the force sensor to screw the indenter on. It is cylindrical, with a radius of 2 mm. This geometry minimizes the adhesive effect of the skin [11], because the contact radius is constant with indenter penetration. The total mass on the force sensor is 4.2 g ( 2g driving platform and 2.2 g indenter).

Most dynamic indentation applications use an electromechanical shaker to move the indenter. In order to reach very small amplitude, we choose to use a piezoelectric translation stage (Piezosystem Jena Inc., Hopedale, USA). We obtain a constant amplitude of motion from 1 to 10 µm for a frequency range of 10 to 60 Hz. It is important to keep a constant amplitude displacement during the frequency scan to put stress on the same area. As the piezoelectric translation stage has a high stiffness compared to the skin, any amplitude disturbance is observed after the contact with the skin. We also work in an open loop.

In order to adapt the device to in vivo experimental conditions, the impedance head and the piezoelectric translation stage are placed on a completely adjustable frame. Indeed, the small force and displacement preclude any manual use. The piezoelectric translation stage is fixed on a high resolution manual translation stage, associated with a digital micrometer that allows controlled sinking of the indenter by about 1 µm. This manual translation stage is put on a rotary plate ring with 30 arc-min resolution so that the indenter will be perpendicular to the skin whatever the area. A camera makes the positioning of the indenter easier. The whole device is put on a mobile adjustable frame with a graniter base. The schematic diagram is shown in figure 2.

The signals are acquired and generated by a computer associated with a National Instruments digital acquisition card and a specific software. Frequency scans are automatically realized. As amplitude strain and force are very small, a breath or heart beat can disturb signals. Thus processing uses Fourier series to extract signals due only to the applied displacement.

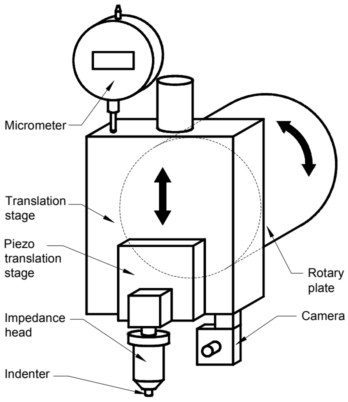

Fig. 2. Developed device.

### *C. Method*

First, a frequency scan is made without any contact to confirm that no disturbance phasingout is introduced by the system. As there is pure inertia on the force sensor, the theoretical phasingout is 180° between force and acceleration. Measurements show a disturbance phasingout of less than 0.5° (fig. 3).

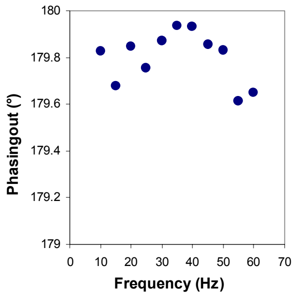

Fig. 3. Phasingout between force and acceleration measured without contact (displacement amplitude 3µm).

The developed device has been tested and validated on pure elastic material: a helicoidal spring. We used a 80 N/m and 100 N/m springs. Measurement at each frequency (fig. 4) and mean values (table 2) on a frequency scan show the validity of the device.

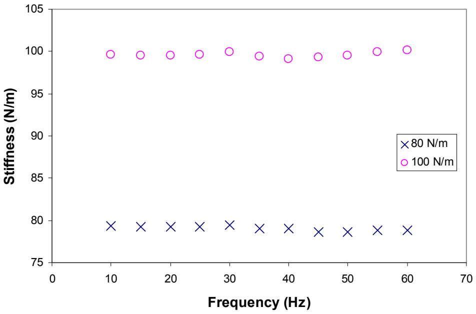

Fig. 4. Stiffness measured at each frequency on two helicoïdal springs (displacement amplitude 3µm)..

| Spring | Stiffness (N/m) | Damping (N.s/m) |
|---|---|---|
| 80 N/m | 79±0.3 | <0.01 |
| 100 N/m | 99.6±0.3 | <0.01 |

Table. 1. Stiffness and damping measured on two helicoïdal spring: mean±standard deviation.

Indenter/skin contact detection is made by measuring the phase angle between the force and displacement signals. Without any contact, the impedance head detects pure inertia; theoretical phasingout is 180°. As soon there is contact, the phasingout decreases, due to the damping of the skin. With this method, the contact is detected with a precision of a few microns.

For each measurement, the subject is placed in a medical chair. As the displacement and the force measured are very weak, it is essential to immobilize the subjects during the frequency scan. They are also two specially designed armrest on the medical chair. Measurements on the cheek have been made using a special headrest.

The device is positioned with the mobil frame, and then adjusted with the translation stage and the rotary plate. Contact is made, the indenter is sunk into the skin, measurements along the frequency are made with a stabilization time for each frequency. Each measurement is made 3 times to confirm reproductibility. Mean value ± standard deviation are given. The first tests have been made on the forearm of 4 men from 23 to 28 years old. The amplitude displacement is about 3µm. The penetration of the indenter is 200µm. The frequency range is from 10 to 50 Hz with an increment of 2 Hz and a stabilization of 3 s for each frequency.

## III. RESULTS

The results show that the stiffness and the damping remain constant (fig. 6) , with a low standard deviation. A Kelvin Voigt model can also model the behaviour of skin. This model is a spring and a dash pot whose physical values do not depend on frequency (fig. 5).

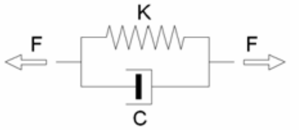

Fig. 5. Kelvin Voigt model with constant stiffness K and constant dash pot C.

The complex modulus has a real part which is independent of the frequency, and an imaginary part which is dependent of the frequency. The values of the real part, the imaginary part for 40 Hz frequency, and the mean value for the complex modulus are given in table 2.

| Subject | K (N/m) | C (N.s/m) | E'* (kPa) | E''* (kPa) | E* (kPa) |
|---|---|---|---|---|---|
| ***1*** | 103.2±13.4 | 0.150±0.045 | 25.8±3.4 | 8.85±0.7 | 27.3 |
| ***2*** | 99.8±10.1 | 0.121±0.082 | 25±1.4 | 8.1±0.25 | 26.2 |
| ***3*** | 47.3±8.9 | 0.087±0.02 | 11.8±2.2 | 5.9±0.6 | 13.2 |
| ***4*** | 128.3±16.9 | 0.186±0.135 | 32.1±4.2 | 9.4±0.86 | 33.4 |

Table. 2. Stiffness, damping, real part, imaginary part and complex modulus on the forearm of 4 subjects.

The results lead us to use the average value on a frequency scan to compare mechanical properties on different subjects. Heterogeneity between these 4 subjects has also been shown; the complex modulus is of 13.2 kPa to 33.4 kPa.

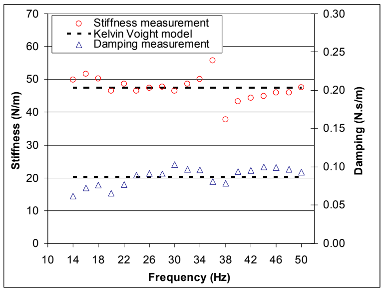

Fig. 6. Comparison between measurement and Kelvin Voigt model on the forearm.

The forearm of one subject was mapped (fig. 7) to evaluate the heterogeneity of the mechanical properties, with measurements on 7 points every 20 mm. The results show (fig. 8) a stiffness variation of up to 110 %.

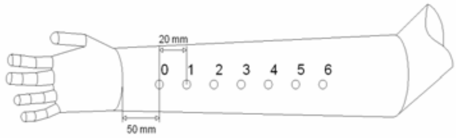

Fig. 7. Forearm mapping.

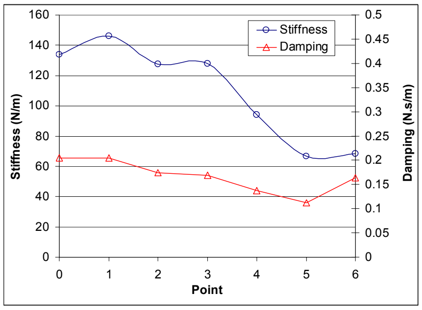

Fig. 8. Stiffness and damping evolution on the forearm.

As the face is the main target of many cosmetic products, the device has been tested on the cheek. Results show (fig. 9) that the Kelvin Voigt model can be applied on this area.

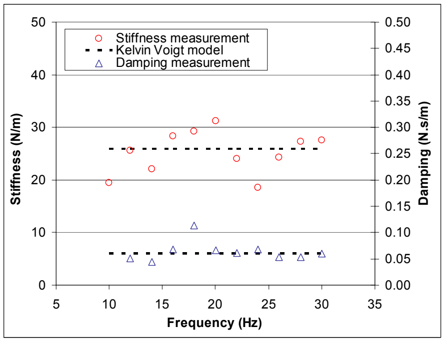

Fig. 9. Comparison between measurement and Kelvin Voigt model on the cheek.

## DISCUSSION

This paper presents a complete device for dynamic indentation with a 1 to 10 µm amplitude strain and a 10 to 60 Hz frequency range. Dynamic Mechanical Analysis is often used on polymers [12]. However, its application to human skin in vivo is unusual.

The results have shown that this device is able to quantify the viscoelastic properties of skin. The stiffness found agree with the literature [13]. The Kelvin Voigt model fits our measurements well. The average value on a frequency scan can be used to compare different subjects.

This new device has many advantages: as stress and strain are very weak, we can say that only the superficial layers are touched. The small contact radius and the fact that no other part are in contact with the skin means that many parts of the body can be accessed. However, as the force and displacement measured are very small, subjects must be immobilized for the duration time of a frequency scan. Studies on effects of cosmetics and medical products and comparison with other devices must be done to determine the capability of dynamic indentation to quantify the evolution of the mechanical properties of the skin.

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