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Moisture Evaluator: a direct measure of fingertip skin hydration during object manipulation

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Background/purpose: The mechanical properties of the fingertip skin are very important when studying dexterous manipulation. These properties are strongly influenced by the level of skin hydration. Currently, there is no device capable of measuring skin moisture during object manipulation.
Methods: Skin moisture levels during object manipulation were measured using the Moisture Evaluator, a probe consisting of gold-covered electrodes connected to a resistor–capacitor circuit. *In vivo* calibration was performed by comparison with measurements obtained using a Corneometer® at two normal force levels (0.2 and 2 N).
Results: Measurements from the Moisture Evaluator were well correlated with those from the Corneometer®.
Conclusion: A new device for evaluating skin moisture at the fingertip has been designed and validated.

Key words: skin hydration – conductance – bioengineering – dexterous manipulation

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Moisture influences the properties of the skin, particularly the coefficient of friction (CF). During dexterous manipulation, changes in skin hydration modulate the mechanical properties of the finger/object interface and alter the minimum pinch force required to avoid slipping of the object. Previous studies have investigated the influence of moisture on skin friction properties. Buchholz et al. (1) reported a significant interaction between the texture of the grasped object and moisture. Smith et al. (2) found that scopolamine increased prehensile force as a consequence of reduced palmar sweating. In the same way, Johansson et al. (3) showed that the variation in CF induced by different levels of skin hydration resulted in behavioral differences during manipulation. These studies have demonstrated the important effect of moisture on the properties of the finger/object interface. An online measurement of moisture at the fingertip would therefore be of major interest to those investigating the role of skin properties in object manipulation.

Skin moisture is a very important parameter in other contexts as well. The fields of cosmetics and dermatology are two areas in which skin hydration is of primary interest. This has motivated the development of various devices to evaluate the moisture content of the skin. Several studies have made a quantitative comparison across different devices measuring skin moisture (4–6). The effect of moisturizers and creams has also been evaluated (7) in order to compare different methods of skin hydration.

The moisture level of the skin is typically measured using one of two principles: capacitance or conductance. Application of these two principles is easy to understand if one considers a simple electrical model of the skin as a resistor in parallel with a capacitor. Because the value of both components is influenced by the water content of the skin, either the resistive component or the capacitive component may be measured. The geometry of the probe electrodes, the frequency of the current, and the design of the oscillating electronic circuit must be adapted to suit the desired measurement principle (8). Barel et al. (9) evaluated two commercial devices, each based on one of these principles: the Corneometer® (capacitance) and the Skicon-200

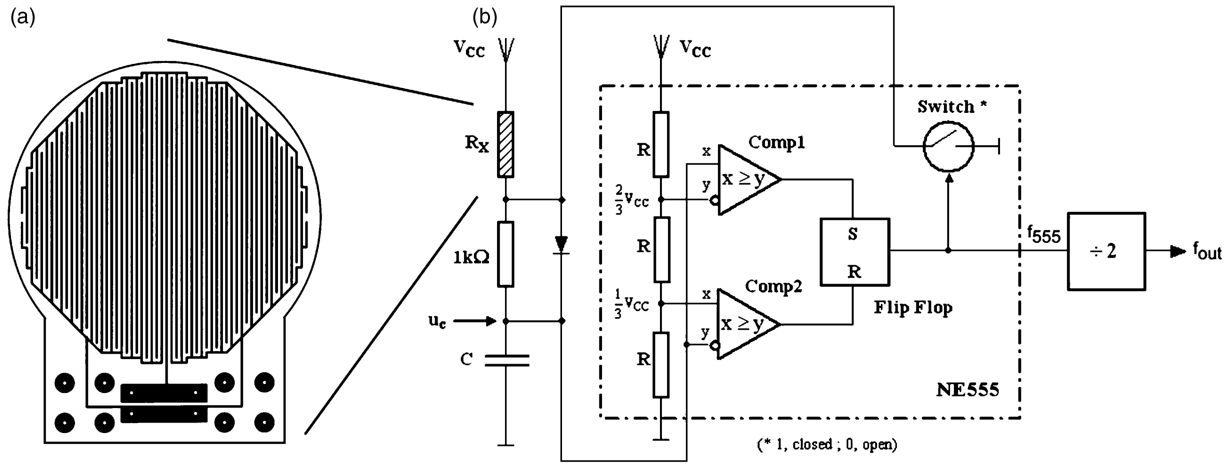

Fig. 1. (a) Network of electrodes that constitutes the probe of the Moisture Evaluator. (b) Diagram of the electronic circuit measuring the conductance of the probe (represented by R_x*):* V_{cc} *is the supply voltage, NE555 is the oscillator that controls the switch by comparing* U_c *with a reference voltage, C is the capacitor that is charged and discharged and* R_x *is the impedance of the probe (influenced by skin moisture). The frequency of the output signal depends on the charging time of C, which is influenced by* R_x*.*

(conductance). They found a good correlation between the methods, with a lack of sensitivity at low levels of hydration for the conductance method and a lack of sensitivity of the capacitance method at very high levels of hydration. Other devices such as the SkinChip, the MoistureMeter, the Nova DPM 9003, and the Dermalab have been tested, calibrated, and are well referenced (4, 5, 10). However, due to the size of the probe, none of these commercial devices enable measurement of skin hydration during object manipulation.

In this study, we present a simple and inexpensive instrument to measure the moisture level of the skin. This device, called the Moisture Evaluator, is based on the conductance principle and is specifically designed for the determination of skin hydration at the fingertip during object manipulation.

Methods

Apparatus

The Moisture Evaluator

The Moisture Evaluator is designed to measure the conductance of the skin surface. The measuring probe (Fig. 1a) has a moderate surface area (12 cm^2) and weight (5 g). It consists of 56 gold-covered electrodes (spacing = 0.89 mm; width = 0.25 mm). The electrodes are alternately connected in a 'comb' configuration. There is a direct galvanic contact between the electrodes and the skin. In order to measure the normal force exerted on the probe during the measurement and to assess its influence on the measurement, the probe is fixed on a force–torque transducer (Mini40 F/T transducer, ATI Industrial Automation, NC, USA). The sensing range for the normal force is ± 120 N with a 0.06 N resolution.

The measurement of conductance is based on a resistor–capacitor circuit. The electronic diagram is presented in Fig. 1b. In this diagram, R_X represents the combined equivalent resistance of the probe and the finger. Inside the Moisture Evaluator is a capacitor C (11 nF) that is charged and discharged at a frequency dependent on R_X. A switch within the NE555 oscillator controls the charge of the capacitor: depending on the capacitor voltage (U_c), the switch is either open (charging) or closed (discharging).

The capacitor voltage evolves differently during these two phases. When the capacitor is charging, U_c increases from 1/3 to 2/3 V_{cc} with a time constant of τ_{ch}. The output logic signal of the NE555 (f_{555}) is low and the capacitor obeys the following equation:

$$U_C = V_{CC}(1 - e^{-\frac{t}{\tau_{ch}}}) \quad (1)$$

When the capacitor is discharging, U_c decreases from 2/3 to 1/3 V_{cc} with a time constant of τ_{de}. The output logic signal of the NE555 (f_{555}) is high and the capacitor voltage is described by:

$$U_C = V_{CC} e^{-\frac{t}{\tau_{de}}} \quad (2)$$

The time constants (τ_{ch} and τ_{de}) can be determined easily. During the charging phase, the 1 kΩ resistor is shunted (via the diode), the capacitor charges through R_X and the time constant

$\tau_{ch} = R_X C$. During the discharging phase, the capacitor discharges through the $1\,k\Omega$ resistor and the time constant $\tau_{de} = R_{1\,k\Omega}\,C$.

Considering the duration of the charging phase T_{ch} and the duration of the discharging phase T_{de}, it has been calculated that $T_{ch} = \tau_{ch}$ ln 2 and $T_{de} = \tau_{de}$ ln 2. The output signal of the NE555 is an asymmetric periodic signal with the frequency

$$f_{555} = \frac{1}{T_{ch} + T_{de}} = \frac{1}{(\tau_{ch} + \tau_{de})\ln 2} \cong \frac{1.44}{(R_X + R_{1\,k\Omega})C} \tag{3}$$

The last stage of the circuit is a frequency divider that is switched at each rising edge. This converts the logic signal to a symmetric square wave to prevent potential acquisition problems. The frequency of the Moisture Evaluator output signal is

$$f_{out} \cong \frac{1.44}{(R_X + R_{1k\Omega})C} \times \frac{1}{2} \tag{4}$$

Therefore, this frequency is a direct measure of the value of the resistance R_X.

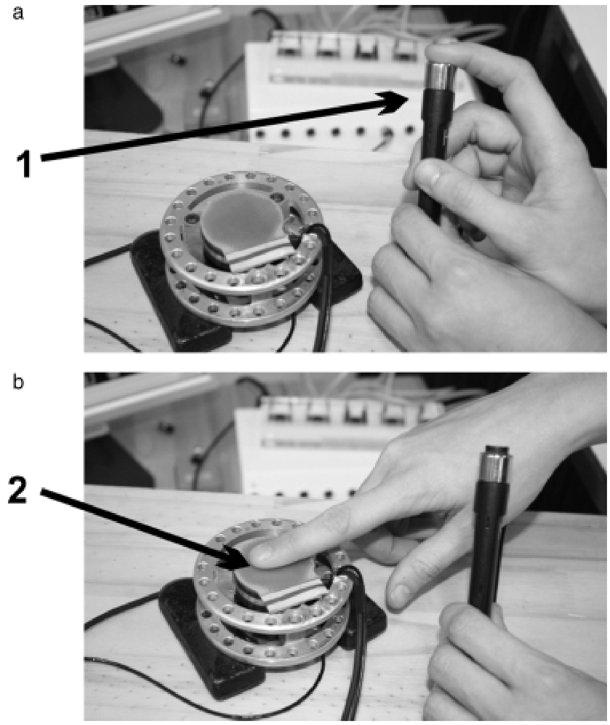

Fig. 2. (a) Measurements of fingertip moisture with the Corneometer (1). (b) Measurement of fingertip moisture with the Moisture Evaluator (2) attached to the ATI force transducer.

The Corneometer® CM 825

In this study, the Corneometer CM825 was used as a reference device. The Corneometer® (CK electronic GmbH, Köln, Germany) has gained worldwide acceptance as an efficient and reliable instrument to measure the water content of the stratum corneum (11).

The Corneometer is based on the capacitance principle and operates at a mean frequency of 1 MHz: 1.15 MHz – very dry; 0.9 MHz – very hydrated (5). The probe consists of a 7×7 mm ceramic tile with many closely spaced gold electrodes that function as capacitor plates (7). The electrodes are covered with a vitrified dielectric material of 20 μm thickness (9). This glass layer prevents any galvanic contact between the electrodes and the skin. The Corneometer is sensitive to the variable dielectric constant of the skin (in contact with the glass layer), which increases with the water content of the stratum corneum. A minimum pressure of 0.8 N is required to trigger the measurement. The measurements are given in arbitrary units (a.u.) ranging from 0 (very dry) to 120 (very wet).

Experiments

Ten healthy Caucasian subjects (five women and five men) participated in this study. Fifteen minutes before the experiment, subjects were asked to wash their hands with soap and water. The experimenter verified that the hands were rinsed and dried carefully. The probes of both instruments (Moisture Evaluator and Corneometer®) were cleaned with alcohol and ether.

As illustrated in Fig. 2, the experimenter measured the moisture of the fingers alternately with the Corneometer® (Fig. 2a) and the Moisture Evaluator (Fig. 2b). Twenty pairs of measurements were obtained at two levels of normal force exerted on the probe of the Moisture Evaluator (0.2 and 2 N).

Data processing

The conductance was determined using a frequency measurement. A higher frequency signal represented increased water content at the skin surface. The frequency of the signal was recorded and reported on a logarithmic scale. For this reason, the output of the Moisture Evaluator is expressed in a.u. corresponding to the logarithm of the measured frequency (expressed in Hz).

All statistical analyses were performed using the Statistica® software package. The coefficients of determination (R^2) of linear regressions were calculated to assess the correlation between the different measures. The analysis of covariance

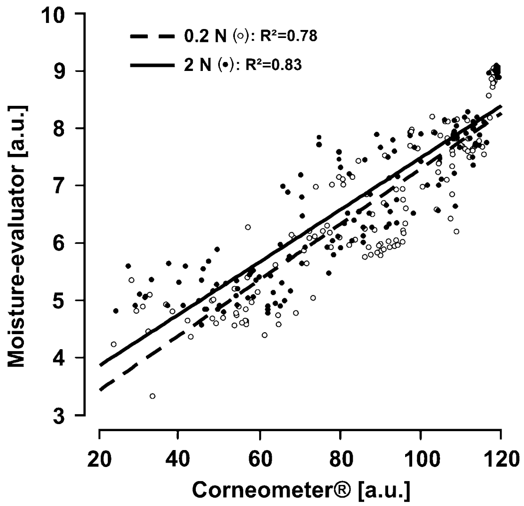

Fig. 3. Relationship between Corneometer® and Moisture Evaluator measurements. Two levels of normal force exerted on the Moisture Evaluator are presented, 0.2 and 2 N.

and the homogeneity-of-slope model have been used to evaluate the influence of normal force on the Moisture Evaluator measurements.

Results

Figure 3 presents the relationship between the Moisture Evaluator and the Corneometer® measurements. The coefficients of determination are large and the correlation is highly significant (0.2 N: $R^2 = 0.78$, $P < 0.01$; 2 N: $R^2 = 0.83$, $P < 0.01$).

The analysis of covariance and the homogeneity-of-slope model have been evaluated considering the Moisture Evaluator measurement to be the dependent variable, the Corneometer® measurement to be the continuous predictor, and the normal force exerted (0.2–2 N) to be the categorical predictor. The analysis of covariance indicated that the normal force had a significant effect ($P < 0.01$) on the parameters of the two regressions. However, the slopes of both regression lines were identical. Indeed, the homogeneity-of-slope model indicated that the normal force does not have a significant effect ($P > 0.05$) on the slope of the relationship between the Corneometer® and the Moisture Evaluator. A significant increase in the normal force (from 0.2 to 2 N) induced a moderate offset of the Moisture Evaluator measurements (average increase of 0.28 a.u.).

Discussion

In this study, we were interested in developing, testing, and validating an original device to measure the moisture level of the fingertip skin during object manipulation. The Moisture Evaluator was designed to utilize the conductance principle and has been compared with the Corneometer®. For the two normal forces tested, the correlation between the measurements from both instruments was strong (0.2 N: $R^2 = 0.78$; 2 N: $R^2 = 0.83$). The coefficients of determination in our study were even higher than those obtained in previous studies comparing different moisture sensing devices (4, 5, 11). The Moisture Evaluator can be considered to be a well-designed system to measure the moisture at the skin surface.

Moisture measurements were compared over the entire range of the Corneometer® (from 20 to 120). This range corresponds to Moisture Evaluator readings between 4 and 10. Figure 3 highlights the reduced sensitivity of the Moisture Evaluator for moisture values below 40 (dry skin) on the Corneometer® scale. This is compatible with the observation that the sensitivity of the conductance method is poor for low levels of hydration (9) and reaches a plateau for that range of moisture, because there is little change in conductance when the skin has a low level of hydration (12). Figure 3 also illustrates the improved sensitivity of the Moisture Evaluator at high levels of hydration. When the values measured with the Corneometer® exceed 115, the output of the Corneometer® saturates (at the maximum reading of 120) whereas the Moisture Evaluator still responds to moisture differences.

In this study, we compared two levels of normal force (0.2 and 2 N) to assess whether a larger normal force improved the electrical contact between the skin and the electrodes, increasing the conductance and skewing the Moisture Evaluator output. The analysis of covariance demonstrated that the force exerted on the probe exerts an influence on the value of the measurement for the Moisture Evaluator. However, the homogeneity-of-slope model indicated that the slopes of the two curves were not statistically different. Therefore, one can consider that a variation of the normal force will only introduce a moderate offset in the measurements of the Moisture Evaluator. Indeed, we found that the mean offset between the two populations was 0.28, which corresponds to only 4.6% of the full range of measurement, suggesting that the influence of the normal force is minor.

The importance of the coefficient of friction (CF) in dexterous manipulation has been emphasized by numerous authors (3, 13–15). Moreover, the influence of moisture on the CF has also been demonstrated. This influence has been studied by comparing only extreme conditions (dry and wet) without measuring a precise value of moisture on a numerical scale (1, 16, 17). The Moisture Evaluator may enable a major breakthrough by providing an on-line measurement of the moisture at the skin surface of the finger and its influence on CF. The Moisture Evaluator accomplishes this by coupling the probe electrodes to the same force/torque sensor used in dexterous manipulation, allowing the on-line acquisition of moisture measurements during object manipulation experiments.

The minor influence of the normal force on the Moisture Evaluator measurements (described above) is of prime importance when studying fine manipulation. Indeed, when an object is held and moved, the normal pinch force varies and is modulated with changing tangential load constraints. Moreover, the occlusion occurring at the interface between the fingers and the object being held influences the skin hydration and therefore the mechanical properties, making an online measurement of moisture at the fingertip during manipulation highly desirable.

The Moisture Evaluator enables the measurement of the water content of the skin surface during the manipulation of objects. It consists of a simple, inexpensive, and adaptable tool. The probe shape and low weight facilitates easy attachment to a force sensor, allowing synchronous recording of moisture levels and mechanical force measurements.

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