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In vivo skin friction measurements

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Synopsis

In the area of SKIN CARE BENEFITS, consumers tend to rate SMOOTHNESS as an important attribute in their overall judgment. This paper describes a TECHNIQUE to measure the FRICTIONAL FORCE resulting from rotating a probe on the skin surface as a function of normal load and speed of rotation. A brief background review on FRICTION THEORY is presented. A number of factors were investigated. The highlights of our findings are as follows.

1. The use of a highly polished stainless steel disc or hemispherical probe produces "wrinkling" or "twisting" of the skin surface during rotation, especially at higher normal loads. The use of an intentionally roughened probe produces friction data which satisfy the simple laws of friction.
2. The force of friction is not a linear function of the normal load as suggested by Amonton's Law, $F = \mu L$, where F is the force of friction, L is the normal load and μ is a constant called COEFFICIENT OF FRICTION. A different expression, $F = KL^n$, was found to describe our results fairly well. K and n are constants. The deviation from Amonton's law is attributed to the elastic behavior of skin.
3. Dry skin produces low friction values. Much higher values are obtained on hydrated skin. A rationale for this behavior is proposed.
4. To produce immediate and significant changes in the friction properties of skin, sufficient quantities of beneficial agents have to be deposited on the surface. Talcum powder and silicone oil reduce the friction force. With silicone oils, fluid or hydrodynamic lubrication is involved.

INTRODUCTION

This paper describes a technique which assesses quantitatively the frictional properties of skin *in vivo* and the effects of product treatment on such properties. Cosmetic products, which are aimed at conferring smoothness to the skin, are thought to perform their function by depositing sufficient amounts of desirable ingredients leading to a perceptible change in the adhesion and friction properties of skin. The perception of such changes is usually subjective, and a fair assessment may not be possible because of the simultaneous interaction of other attributes. Obviously, a method to assess skin friction properties quantitatively not only offers a better way of generating basic information on the condition of untreated skin, but it could also provide valuable guidelines in the course of developing new products aimed at producing a desirable tactile feel.

The technique to be described in this paper features a cylindrical metal probe, which contacts the skin surface under a given normal load. The probe can rotate within a wide range of speeds, and the resistance to the rotating motion can be measured directly via a torque measuring device. Specifically, we have set out to examine the applicability of the general laws of friction, derived mainly for metallic materials, to human skin as a substrate. A basic premise of modern friction theories relates to the distinction between the real area of contact between sliding materials and the geometrical area. The real area of contact is much smaller than the geometrical area due to surface roughness. This point has been examined in some detail using a rough and highly polished probe made from the same material. Also, the effect of lubricants (talcum powder and silicone oil) has been examined and an attempt was made to elucidate the lubrication mechanism of these materials.

THEORETICAL BACKGROUND

The coefficient of friction μ between two solids is defined as F/L, where F denotes the frictional force and L is the load or force normal to the surfaces. When μ is constant, $\mu = F/L$ is known as Amonton's law and expresses two important observations: (1) the friction force is proportional to the normal force; and (2) the friction force is independent of the apparent area of contact.

There is abundant evidence that even microscopically smooth surfaces are irregular on a molecular scale of distance. As a result of irregularities, two surfaces brought into contact will touch only in isolated regions. The true area of contact is then much less than the apparent area; it can be estimated, for example, from a measurement of the electrical conductivity between the two solids. It is also known that high local temperatures can develop during rubbing, as well as high local pressures, which can lead to plucking out of portions of the softer material by the harder one (1–4).

As the two surfaces are brought together, the pressure is large at the initial few points of contact, and deformation immediately occurs to allow more and more contact to develop. This plastic flow continues until there is a total area of contact such that the local pressure has fallen to a characteristic yield pressure P_m of the softer material. Thus, around each region of contact, there is a plastic zone, with further elastic deformation outside (2). The actual contact area is then determined by the yield pressure, so that

$$A = L/P_m \tag{1}$$

In a typical measurement of friction, a slider is pressed against a stationary block and the force F required to move the slider is measured. This force, in general, will consist of 2 terms. First, there is the force F required to shear the junctions at the points of actual contact. This is given by

$$F = AS_m \tag{2}$$

where S_m is the shear strength per unit area. The second term, F_1, is the force required to displace the softer material from the front of the harder one. With metals of different hardness, the harder one, if used as a slider, will plow a track in the softer, and F_1 is, therefore, a work term associated with this plowing action. In a general way, one expects F_1 to be proportional to the width of the slider, i.e.

$$F_1 = K A_1 \tag{3}$$

where A_1 denotes the width of the plowed track. Usually, the plowing term is important only for the case of a hard material rubbing against a soft one; if both are hard, the friction is due mostly to the shear term. As an approximation, then, A may be eliminated from equations (1) and (2) to give

$$F = L\,(S_m/P_m) \tag{4}$$

or

$$\mu = S_m/P_m = \text{constant} \tag{5}$$

This is Amonton's law as stated earlier. A point in connection with this law is that the two quantities, S_m and P_m, represent the resistance to plastic flow of the softer of the contacting materials to shear and compression, respectively.

The coefficient of friction may also depend on the relative velocity of the two surfaces. This will, for example, affect the local temperature, the extent of work hardening of metals, and the relative importance of the plowing and shearing terms. These facts work out such that the coefficient of friction tends to decrease with increasing sliding speeds (4, 5) contrary to Coulomb's law, which holds that μ should be independent of sliding velocity. At very low speeds, the effect is small.

A number of friction studies have been carried out on organic polymers in recent years (4–6). The detailed results show some serious complications, however. The coefficient of friction was shown to be dependent on the load as has been illustrated, for example, in the case of a copolymer of hexafluoroethylene and hexafluoropropylene (7), where it was suggested that the area of contact is determined more by elastic than by plastic deformation. The difference observed between the static and kinetic coefficients of friction (the force required to initiate sliding of the load gives μ_s, where s refers to static, and the force requires to sustain the motion gives μ_k, where k refers to kinetic) was attributed to the transfer of an oriented film of polymer to the steel rider used in the experiment during sliding and to low adhesion between this film and the polymer surface.

An important aspect of friction measurements in relation to cosmetic applications is the friction between lubricated surfaces. Two limiting conditions exist where lubrication is used. In the first case, the oil film (lubricant) is thick enough so that the surface regions are essentially independent of each other, and the coefficient of friction depends on the hydrodynamic properties, especially the viscosity, of the oil. Amonton's law is not involved in this situation, nor is the specific nature of the solid surfaces. As load is increased and relative speed is decreased, the film between the two surfaces becomes thinner and increasing contact occurs between the surface regions. The coefficient of friction rises from the very low values possible for fluid friction to some value that is usually less than that for unlubricated surfaces. This type of lubrication, i.e., where the nature of the surface region is important, is known as boundary lubrication and involves a strong physical adsorption of lubricant on the surface or even a surface chemical reaction leading to a very strong bond between the lubricant and the substrate. The general feature of friction between lubricated surfaces is usually represented by what is known as the Stribeck curve, which is a plot between the coefficient of friction and the so-called Sommerfeld number, $\eta V/P$. η is the viscosity of the lubricant film, V is the speed of sliding, and P is the normal load per unit area. This

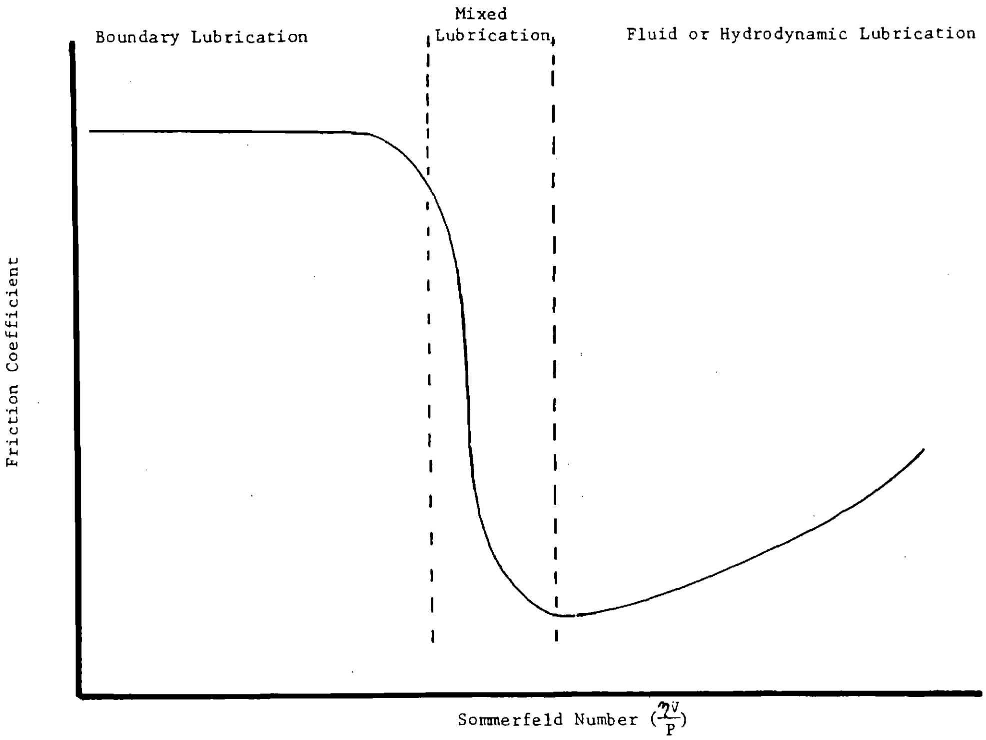

Figure 1. Stribeck curve showing the relationship between friction coefficient and the Sommerfeld number

relationship is represented schematically in Fig. 1. It has been shown that the value of μ in boundary lubrication depends greatly on the state of the adsorbed film and that, generally speaking, the film must be in a condensed state to give a low coefficient of friction. A number of models have been suggested to explain the mechanism of boundary lubrication (1, 4, 8, 9).

PREVIOUS FRICTION MEASUREMENTS ON SKIN

Few papers have been published on the frictional characteristics of skin. Naylor (10) measured the friction of a polyethylene ball rubbing against the skin. He found that the friction was higher when the skin was damp than when it was either very wet or dry. Appeldoorn and Barnett (11) have observed other distinctive frictional characteristics of skin as follow: (1) skin friction is "relatively high;" (2) a small amount of talcum powder greatly reduces skin friction. This is well known, but it is not a characteristic of the friction of other systems such as steel-against-steel, where talc increases friction; and (3) the skin friction is higher on a smooth surface than it is on a rough surface. This behavior is just the opposite to that normally encountered, but it can be verified by rubbing one's finger on a microscope slide. The friction is much greater on the clear glass (smooth) part than on the ground glass (rough) part.

Although Appeldoorn and Barnett have not conducted any *in vivo* work, they found that an *in vitro* model combining a rubber ball and a rotating stainless steel cylinder correlates well with their observations on the behavior of skin friction. They concluded that the property of skin that gives it the unusual and characteristic behavior is not its roughness nor chemical composition, but its "flexibility." Like rubber, the skin can flex to conform to the shape of another surface. This gives it a relatively large area of contact and, therefore, a high coefficient of friction as compared to the relatively unflexible metal or plastic materials. These results have been confirmed by Prall (12) and by Comaish and Bottoms (13) on skin under *in vivo* conditions.

EXPERIMENTAL TECHNIQUE

Earlier experimental techniques for skin friction measurements have been reviewed by Prall (12). Traditionally, friction measurements involve the sliding of a probe over the skin and the force is determined as a function of load. Prall describes a friction dynamometer which features a constant-thrust friction head whereby a standard ground glass disc was pressed against the skin with a force of 200 g/cm^2. The friction head was attached to the shaft of an ac motor, which was energized by a variable transformer. In use, the friction head was presented to the skin, and the power to the motor gradually increased until the friction head just started to rotate.

In this work, we employ a modified Haake viscometer (RV-1)* to measure the friction behavior of skin *in vivo* with the help of a rotating stainless steel probe in contact with the arm (or any other part) surface. Preliminary experiments have shown the need for controlling the contact pressure between the skin surface and the probe. To this end, a special probe assembly was designed such that a constant load was maintained in contact with the skin surface in the course of the experiment. The assembly is depicted schematically in Fig. 2. The assembly features an adapter which fits tightly onto the shaft of the Haake measuring head. The part carrying the load and the probe is precisely machined so that it slides smoothly over the cylindrical adapter. The extent of vertical movement of the probe attachment is controlled by the size of the slit and a protruding knob on the adapter body. Loads can be added to the assembly by screwing on metal discs of known weight. The load is, thus, suspended and floats freely between the two ends of the slit. This design offers a convenient means to ensure a constant load contacting the skin. The panelist is only required to maintain the knob approximately in the middle of the slit during the experiment.

The measuring principle is as follows. The control console of the Haake RV-1 houses the operating controls, synchronous motor, electrical circuitry, and indicating meters. It drives the measuring head and the meter reading indicates only the torque induced by the frictional resistance to the rotating probe, and not the friction in the transmission. Torque is measured by the angular displacement of a creep-resistant torsion spring, mounted between two concentric conical shafts. The displacement angle is converted into an electrical signal by means of a high-precision potentiometer. The voltage output of the potentiometer is linear to the angular displacement of the spring. Thus, the torque exerted on the probe is proportional to the signal registered on the console meter.

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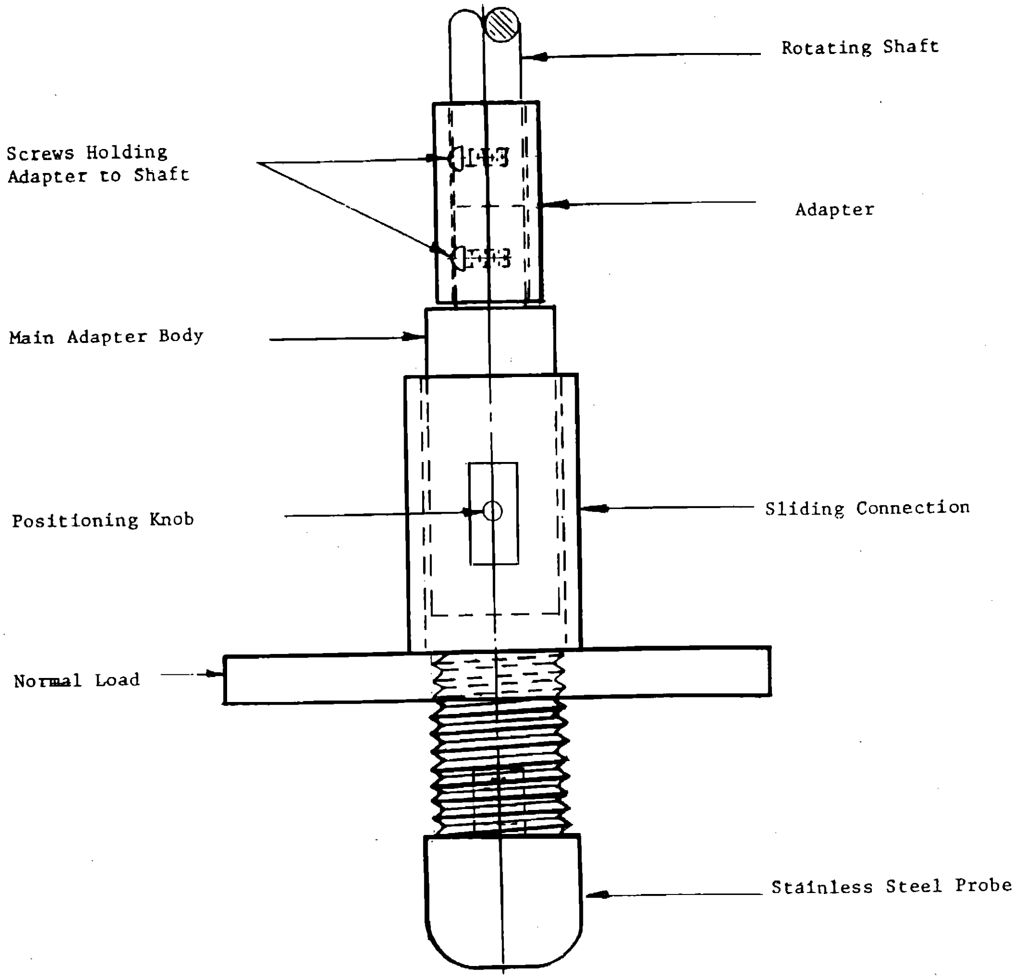

Figure 2. Friction probe assembly

We have calibrated the scale readings in terms of absolute force by determining the scale response to different weights attached to the probe with a thread. The measuring head was laid horizontally on a table such that the probe assembly protruded over the edge. Measurements were conducted at the lowest speed available (3.6 rpm) and care was taken that the thread windings did not pile up on the probe. The calibration curve obtained representing the force versus load was linear. Joy, Machin, and McGaw used a similar technique employing a modified Haake viscometer for measuring skin friction properties *in vivo* (14).

RESULTS AND DISCUSSION

A general view of the set-up is shown in Fig. 3. As will be discussed below, the state of skin hydration affects its friction properties, and, hence, it was necessary to conduct the measurements under controlled temperature and humidity (22°C and 55 per cent rela-

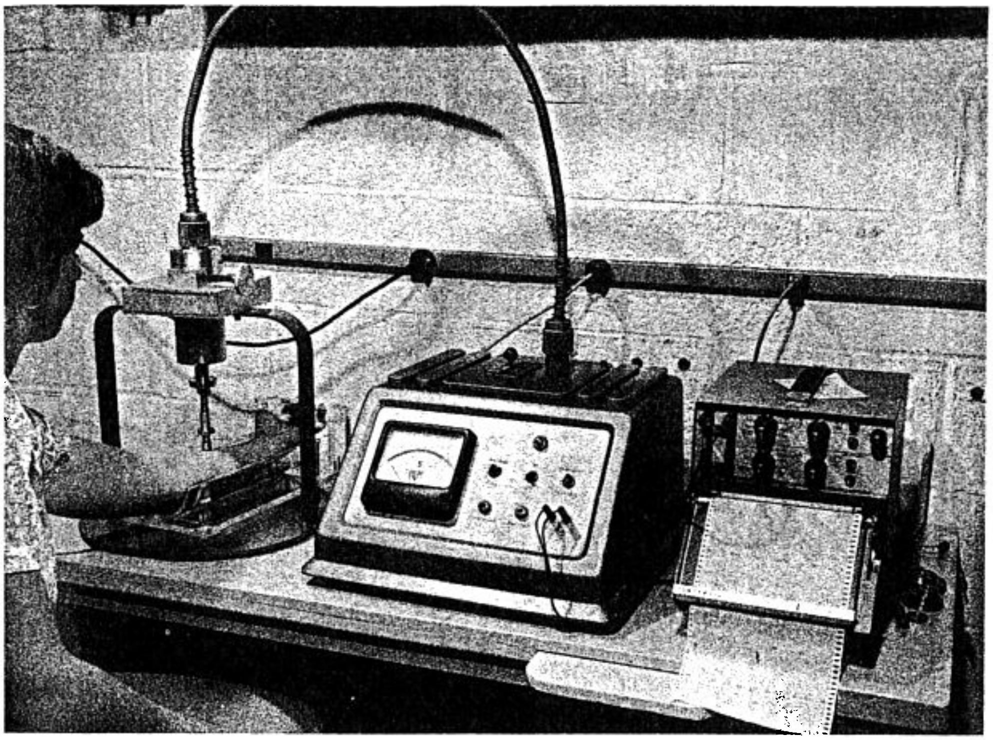

Figure 3. Friction measurement set-up

tive humidity). In general, measurements can be carried out on almost any part of the body, but for the sake of convenience, the test site used in this study was restricted to the volar forearm of about 20 female panelists ranging in age from 20 to 50 years. Normal loads of 0 to about 200 g were used. The friction force was determined 3 to 4 times at any given load to compute an average value. A number of factors were examined and these will be discussed separately.

EFFECT OF PROBE SHAPE

Initial attempts, using a disc-shaped highly polished stainless steel probe to measure the friction force, led to an interesting observation. It was found that in the course of the measurement, the friction increased with time accompanied by a certain degree of discomfort to the panelist, especially at higher loads. A closer examination of the skin in contact with the rotating disc revealed obvious "wrinkling," leading to what could be described as a "pinching-effect." This type of probe was discarded, and to alleviate this difficulty, we resorted to the use of a hemispherical probe (radius 0.6 cm). Two such probes were employed in this work; one probe was highly polished, and the other was intentionally roughened using emery paper. Both probes were of the same dimensions and made of stainless steel. The response of the two probes at a given load is shown schematically in Fig. 4, which demonstrates clearly the difference in behavior of the

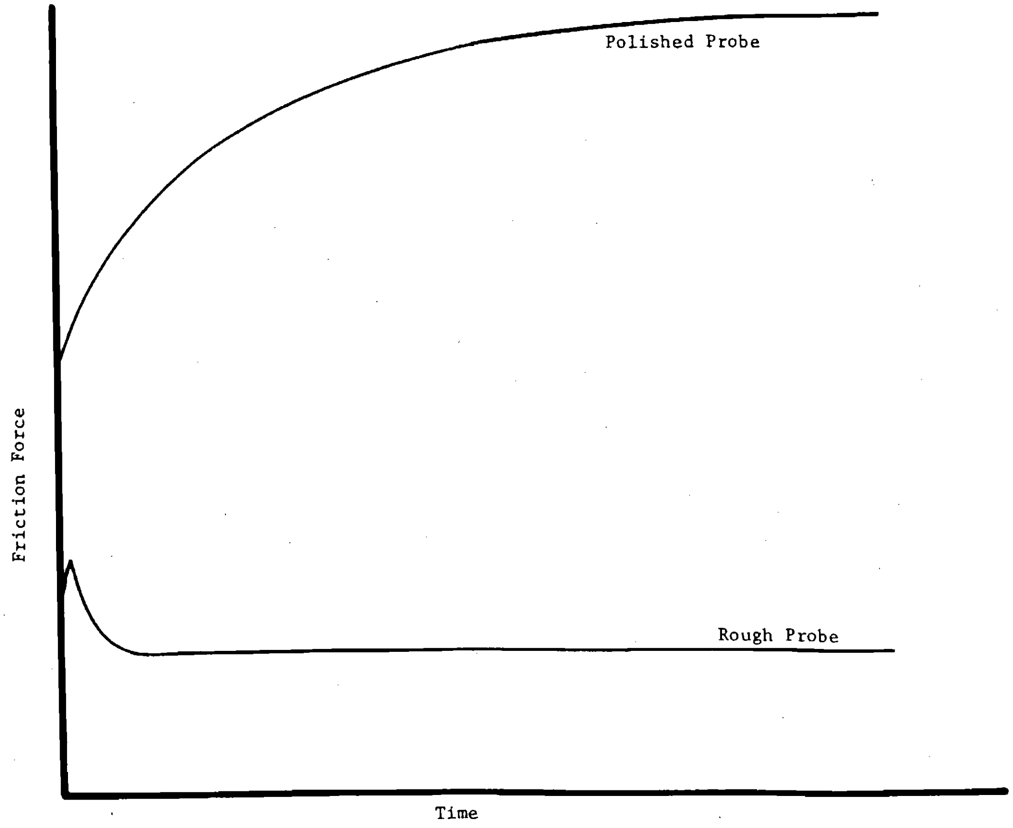

Figure 4. Schematic response of polished and rough probes during friction measurements on human skin *in vivo*

two probes. In the case of the rough probe, it can be seen that as the probe starts rotating, a maximum value for the force of friction is recorded which quickly tapers off to a constant value within a few seconds. The polished probe, on the other hand, produces a friction force—time profile which indicates an instaneous large response on the force axis, followed by a continual increase and a leveling off after a few minutes (3 to 4 min). Close inspection of the skin contacting the rotating probe revealed that while no "pinching-effect" was felt by a panelist, there was obvious wrinkling of the skin. The degree of wrinkling or twisting of the skin was found to be related to the load used in a given measurement. Thus, at low loads (*ca.*, 50 g) no wrinkling was observed with the polished probe, whereas, the disc-shaped probe produced wrinkling even at lower loads. Skin wrinkling was not observed with the rough probe over the whole range of loads used, and the results obtained with this type of probe were reproducible. Rather large fluctuations in the force values were observed with the polished probes, especially under high loads.

The formation of wrinkles is a complicating factor in skin friction measurement, since it is doubtful that the data obtained under such conditions relate to the inherent friction properties of the skin corneum. This point will be discussed further below. We

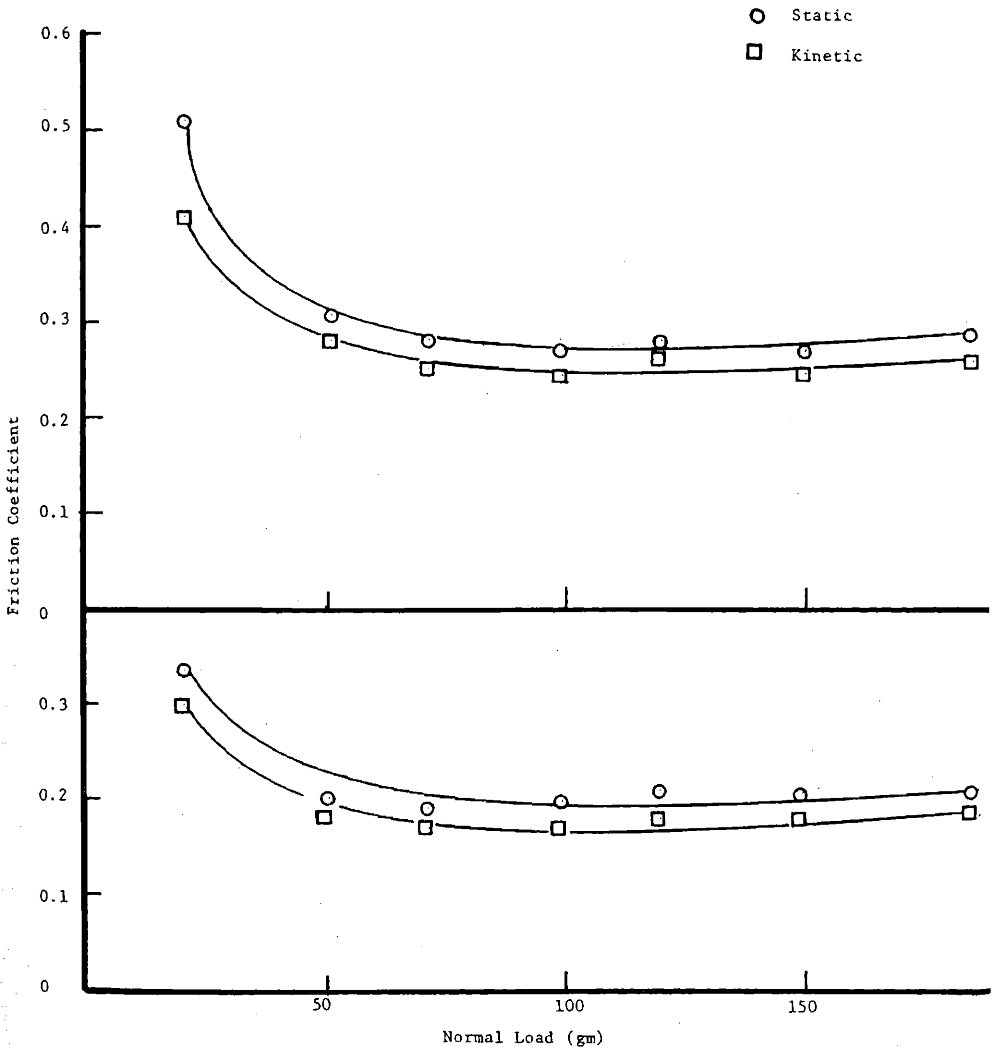

Figure 5. Static and kinetic friction coefficients as function of normal load

have, therefore, focused on the use of the rough probe, since the results obtained with this probe seem to conform in a much simpler way to the basic laws of friction.

The dependence of the coefficient of friction on load is shown in Fig. 5 for two panelists. The data are presented as the static (μ_s) and kinetic (μ_K) coefficient of friction. μ_s was determined from the maximum value of the friction force versus time curves and μ_K relates to the value of the force of friction after attainment of an equilibrium value (Fig. 4). It is clear from Fig. 5 that the friction force is not related linearly to the load, and, hence, Amonton's law is not obeyed.

All panelists examined showed the same general relationship as given in Fig. 5. These data confirm Comaish and Bottoms' findings that the friction coefficient for human skin *in vivo* increases as the load decreases (13).

One can recall that Amonton's law expresses the relationship between the friction force and load for systems in which only plastic deformation occurs at the contact points. The nonlinearity of the force-load relation has been attributed to contributions of other mechanical components in the process of deformation such as elasticity. A simple equation describing the force-load relation under these conditions was proposed by Bowden and Tabor (2), and has the form

$$F = KL^n \tag{6}$$

where K and n are constants. The value of n ranges from 0.66 to unity. When $n = 1$, the above equation expresses Amonton's law. We have attempted to fit our data to the above equation using regression analysis with the help of a computer. Eleven cases were analyzed to evaluate the determination index (a measure of the goodness of fit) and the values of the regression coefficients at 95 per cent confidence limits. The results are given in Table I. A more detailed example of the computational analysis where the actual friction force values are compared with values calculated from equation (6) is presented in Table II.

Table I
Regression Analysis of Friction Data Fitted to the Equation $F = KL^n$ at 95 per cent Confidence Limit

Panelist Number	Index of Determination	Regression Coefficients	
		K	n
1	0.971	0.70	0.79
2	0.981	0.66	0.71
3	0.996	0.82	0.67
4	0.950	0.45	0.80
5	0.975	0.28	0.90
6	0.986	0.68	0.68
7	0.985	0.36	0.87
8	0.994	0.43	0.75
9	0.959	0.18	0.96
10	0.979	0.41	0.79
11	0.988	0.59	0.76

Table II
Example of Data Fitting According to the Equation $F = KL^n$ For Panelist Number 3 (Table I)

Actual Load (g)	Actual Friction Force (g)	Estimated Friction Force (g)	95 Per Cent Confidence Limits
20.9	6.25	6.21	5.77–6.68
50.5	11.25	11.18	10.74–11.65
71.4	14.38	14.10	13.63–14.58
98.9	16.56	17.52	16.93–18.13
119.8	19.38	19.92	19.18–20.68
149.4	23.75	23.08	22.09–24.11
187.7	27.50	26.88	25.53–28.30

In general, the equation seems to satisfy the experimental data reasonably well. A theoretical interpretation of the above equation has been suggested by Bowden and Tabor (2), based on the simple premise that if the shearing strength, S_m is constant

$$F = AS_m \tag{7}$$

then, the variation of the friction force with the load is due to the way in which A (the real area of contact) varies with the load, i.e.,

$$A = K_1L^n \tag{8}$$

The differences in behavior of the polished and rough probes could be ascribed to the difference in the number of contact regions involved. With the polished probe, it would be expected that a much larger number of contact points would be established with the skin surface. Thus, upon rotating the polished probe on the skin substrate, the skin is "pulled" along, conceivably as a result of high adhesion. Continuous rotation should lead to the formation of wrinkles. The formed wrinkles will present an added resistance to the motion of the polished probe, which would be a function of the rate of "wrinkling." The measured value of the force under such conditions will not reflect the inherent friction properties of the substrate. The rough probe on the other hand, does not produce wrinkling because of the much smaller real contact area with the skin, so that the skin is not pulled along as the probe rotates, presumably because of the lack of adequate "grip."

Friction force measurements with the rough probe were highly reproducible at the lower loads showing variation of 2 per cent about the mean, but the variation increases to about 10 per cent at the higher end of the load range.

We have also examined the state of skin after contact with the rotating probe for 3 min for any possible plowing action or disruption in the surface. As mentioned earlier, the combination of a hard sliding probe on a softer substrate may lead to plowing. Scanning electron micrographs were taken of the same skin area before and after probe contact, using standard replicating procedures. Fig. 6 shows two such sites of a female panelist. There is no evidence of plowing or surface disruption as a result of contact of the rotating probe with the skin.

EFFECT OF SPEED OF ROTATION AND SITE-TO-SITE VARIATION

A study was made of the effect of the speed of rotation at a given skin site on the coefficient of friction under constant load. The speed ranged from 3.6 to 583 rpm. A number of measurements were also conducted to establish any variation in the value of the coefficient of friction along the volar forearm. Such measurements were usually carried out at a given speed of rotation and load. The general conclusions indicate that the effect of speed of rotation is negligible over the range examined, and that there is no site-to-site variation on the volar forearm if the measurements are restricted to the larger area close to the elbow.

EFFECT OF SKIN HYDRATION

After initial determination of the coefficient of friction at a given speed and load, a number of panelists were asked to rinse their arm with water and blot away any excess.

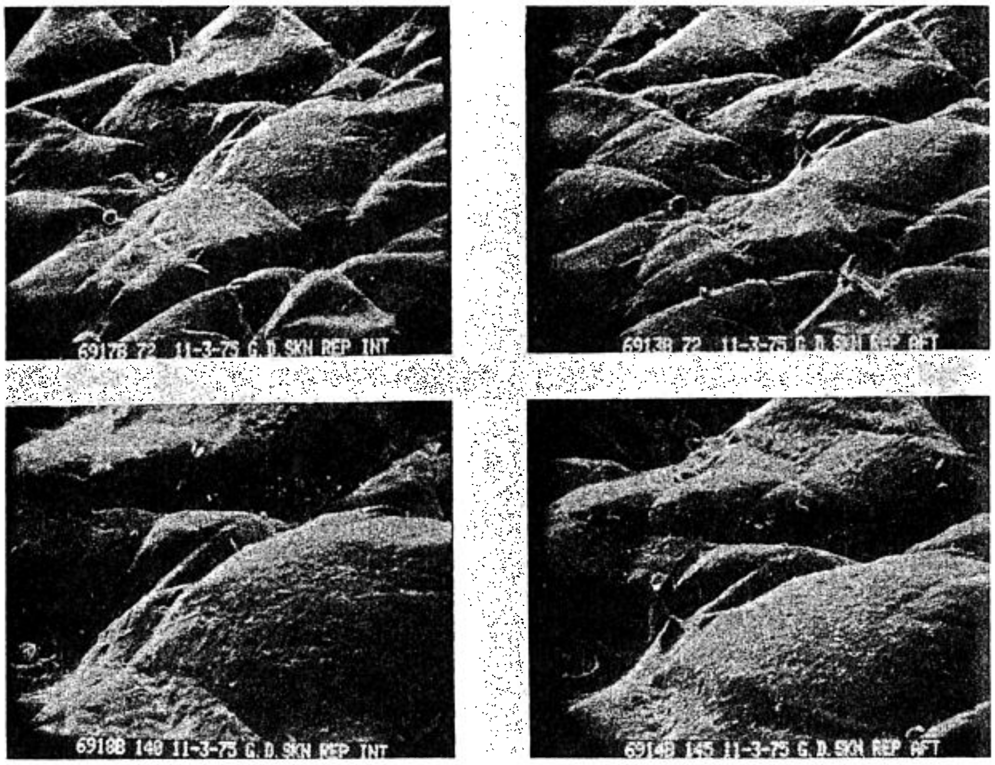

Figure 6. Photographs coded 6917 B and 6918 B show two different sites on skin surface *before* probe contact. Photographs coded 6913 B and 6914 B show the *after* effect

Measurements of the friction coefficient were then repeated immediately on the same test site. A 2–3 fold increase in the coefficient of friction was recorded on most panelists using the rough probe. It is interesting to note, however, that normal values of μ, obtained before rinsing, were again achieved after about 2 min. It is also worth noting that during the first measurement, immediately after rinsing and blotting, the rough probe exhibited a response similar to the polished probe, i.e., an increase of the force of friction with time. Subsequent measurements showed a normal response. The degree of wrinkling increased substantially when using the polished probe on the hydrated skin. These observations can be explained by assuming a substantial decrease in the compression modulus of skin due to presence of water, leading to an increase in the size and, perhaps, the number of the junction zones (hence, an increase in the real contact area) which would ultimately increase the coefficient of friction. The decrease in the value of μ, after about 2 min, to the original value, indicates a return of the mechanical properties to the normal values due to the fast evaporation of water from the skin surface. These findings support Appeldoorn and Barnett's observations concerning the effect of skin hydration on friction properties (11).

Table III
Comparison of Friction Values on "Normal" and "Dry" Skin
Load 98.9 g, Rotation Speed 2.03 cm/sec

	Friction Force (g)[a] Polished Probe	Friction Force (g)[b] Rough Probe
Normal Skin	62.5	16.0
Dry Skin	37	11.6

[a] Values after 20 sec.
[b] Values refer to kinetic friction force.

EFFECT OF SKIN DRYNESS ON FRICTION PROPERTIES

Because of the difficulty in inducing skin dryness under laboratory conditions, it was not possible to conduct an exhaustive study on the effect of dryness. We were able, however, to conduct some measurements on 1 panelist suffering from a severe case of skin dryness, which was obvious even to the untrained eye. The dry site was located on the dorsal forearm, and its extent was rather restricted. Friction measurements were made on a "normal" and the "dry" site using the polished and rough probes. The data are given in Table III. It can be seen that a substantially lower value of the force of friction is found on the dry site with both probes. A much larger decrease is observed with the polished probe, however.

EFFECT OF TALCUM POWDER

Before-and-after friction measurements were conducted using talcum powder as a solid lubricant on 7 panelists. The polished and rough probes were used at a speed of 32.4 rpm and 98.9 g normal load. As expected, some wrinkling was observed on the untreated skin with the polished probe, and the force readings were arbitrarily taken after 20 sec. A decrease averaging 50 per cent in the friction force was observed with the polished probe after application of talcum powder. No wrinkling of the skin or increase of the force with time was observed in the course of the measurement.

Little or no decrease in the friction force was registered with the rough probe after application of talcum powder. The amount of talcum powder applied to the skin was enough to cover the surface with a thick film, such that direct contact between the probe and the skin substrate was not possible. The effect of talcum powder can be attributed to its low S_m value and adhesion to the stainless steel surface; hence, a lower friction force would be expected. The fact that the same values for the friction force were obtained with the polished and rough probes after application of talcum powder, lends support to the notion that a film of talcum powder was transferred to the probe surface such that the measured values of the force reflect the property of the talcum/talcum system.

EFFECT OF SILICONE OIL

An investigation of the effect of silicone oil (polydimethyl siloxane) as a fluid lubricant, when applied as a thick film onto the skin surface, on the friction properties was

Table IV
Effect of Silicone Oil Viscosity and Probe Speed on the Friction Force. Load 98.9 g. Polished Probe

Speed (rpm)	Friction Force[a] (g) Untreated Skin	Viscosity of Silicone Oil (cks) 100	1,000	10,000
3.6	30.6	6.5	7.5	8.5
10.8	30.8	7.5	11.9	15.0
32.4	30.7	9.4	15.0	28.8
67.2	30.8	11.9	19.6	37.5

[a] Values at 20 sec.

conducted on 10 panelists. The effects of speed of rotation of the probe and of the viscosity of the silicone oil were examined in some detail to identify the mechanism of lubrication involved. The relevant data for 1 panelist have been compiled in Table IV. The results obtained indicate that the presence of silicone oil decreases substantially the friction force compared to untreated skin and that the mechanism involved is fluid or hydrodynamic lubrication, i.e., the friction force is dependent on the bulk properties (viscosity) of the lubricant. Both probes behave similarly in the presence of a fluid lubricant, both qualitatively and quantitatively.

A number of important points emerge from the above findings regarding *in vivo* friction measurements on skin as follows:

1. The effect of the surface condition of the probe. It has been shown that the type of finishing given to the probe surface has an important qualitative and quantitative effect on the results.

2. Low friction values for untreated skin do not necessarily mean a smooth skin condition. As has been shown in this work, obviously dry skin gave lower friction force values than seemingly normal skin. It is, therefore, necessary, before assigning any practical significance to the effect of product treatments on skin condition, to establish a meaningful correlation between instrumental measurements and what consumers perceive as an acceptable skin condition. This can be achieved by using a large panel and trained judges to help determine the range of the friction coefficients which describe the different skin conditions.

3. In order to bring about perceptible changes in the friction properties of skin through product application, it is obvious that a sufficient amount of some beneficial ingredient should be deposited on the surface. The simplest approach is to use the product directly as in the case of creams and lotions, for example. As suggested by this work, the properties of the residual film will probably have a direct bearing on consumer acceptability. Such products will probably exhibit hydrodynamic lubrication, and, hence, the viscosity of the applied film will be of considerable importance. Again, it will be necessary to define the optimum ranges of an acceptable friction coefficient under these conditions via panel testing. A very low value of the friction coefficient may be associated with "slippery feel" and too high a value will most likely be associated with "sticky feel."

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