

# MECHANICS OF TOUCH SENSATIONS

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## Executive Summary

In this report we considered the factors controlling tactual sensations when aqueous solutions are placed between fingers, between fingers and the palm of the hand or when these contacts are made through another media, say, contact lens.

We noted that touch sensation arises from the neural signals of the nerve ending receptors beneath the surface of the skin in response to the two forces acting on the surface of the skin: the pressure force normal to the touching surface and shear force tangent to the surface. The normal force between the fingers and palms, separated by an aqueous solution, is experienced as pressure when the fingers are pressed together or as tacky or sticky when the fingers are pulled apart. The shear force gives rise to the sensation of slipperiness or friction when the fingers are rubbed against each other.

The experiences of stickiness and slipperiness depend strongly on the thickness of the liquid film between the sliding fingers. For thick films which may occur when the applied force between the fingers is small and the liquid is very viscous, the sensation can be solely characterized by the bulk viscosity of the liquid in the lubricating film.

Thin molecular films give rise to special sensations because they are adsorbed on the skin and are effected by both the skin and fluid. The exact chemistry and mechanics of these ultra thin lubricating films is not perfectly understood. The lubricating film in this state is subject to short range forces like Van der Waals forces which endow the film with properties which depend on the boundary surfaces as well as the chemical composition of the liquid.

We believe that the most important factors in characterizing touch sensation are the adsorption of surface active agents (surfactants) in the aqueous solution onto the oily skin surfaces. Classification of surfactants can be achieved as we reported here, for example, anionic surfactants (like sodium dodecyl sulphate) give rise to a sensation of great slipperiness.

The problem of touch sensation in thick films is not difficult. The bulk viscosity of a liquid can be easily measured with standard methods. The best way to get a quantitative measure of sensation in thin films is to measure the coefficient of static friction on the skin or skin substitute. The measurement of static friction on flat surfaces is not hard, but this measurement may not be possible on living skin. For a skin substitute, any leather-like substance which adsorbs skin-like oils would work.

## **Purpose of the Research Project**

The problem here is to define the characteristics that create the sensations perceived by feeling an aqueous solution with the forefinger, palm and thumb, and to correlate the feeling of sensations with measurable physical properties of the fluid, fluid-skin interactions and the dynamical conditions under which sensations are felt. The goal is to understand also skin–aqueous solution and skin–soft contact lens sensations in terms of mechanical measurements, and to identify the tools to provide accurate measurements of these physical properties.

## **Technical Description and Analysis**

### **I. Introduction**

The problem here is to correlate the feeling of sensations using different aqueous solutions with measurable properties of the fluid, fluid-skin interactions and the dynamical conditions under which sensations are felt. The goal is to understand also skin–aqueous solution and skin–soft contact lens sensations in terms of mechanical measurements.

The sensations under consideration are psychophysical and are not precisely defined. To understand these sensations, it is best to make a list: rough and smooth, sticky, tacky, slippery, slimy, oily, hard, soft, cold, hot. We believe that the determining factors in these perceptions of sensations are mechanical and that different individuals will agree with the perception that a certain aqueous solution is, say, sticky or slippery when the materials and dynamic conditions under which the sensations are experienced are well controlled. This means that the sensations are controlled by the natures of the objects being felt, and subject-object interactions and not by subjective experience. It is possible to identify the controlling parameters and to measure them.

### **II. Previous literature**

There is a huge literature on tactual perception written by researchers in biology, medicine and psychology. An excellent summary of such literature can be found in a compilation of review paper in the volume “Tactual Perception. A Source Book” edited by W. Schiff and E. Foulke (see the references). Some of this literature is useful but only in a secondary way as background in our attempt to characterize sensations with mechanical and

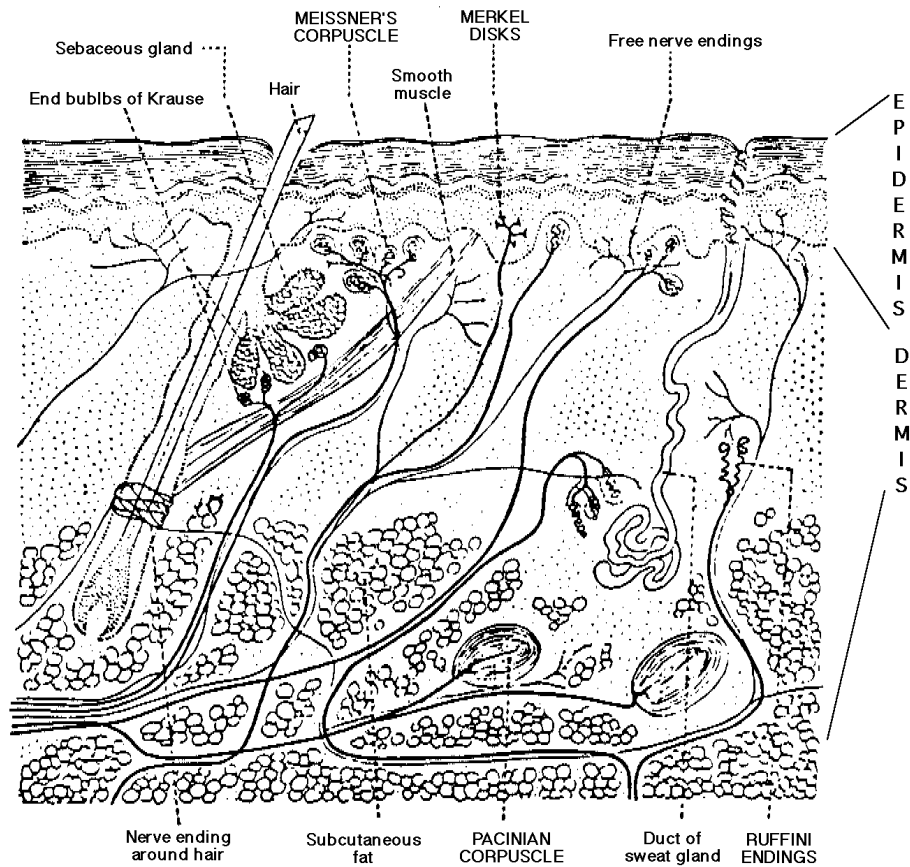
material properties. We shall call this literature “psycho-physical.” The studies try to correlate the perceptions of texture among sample groups with some gross properties, such as grooves, roughness, hot and cold, hardness and softness. Surveys are taken about perception and in some papers there are discussion of the sensor properties of skin and nerves. None of these studies aims to correlate the perception of sensation in aqueous solutions with the material properties of the solution like density, viscosity, the effect of added polymers, surfactants and the dynamical properties of lubrication and friction. The difference we have just described in the difference between an engineering approach and psychological approach. It is not useful to review the vast psycho-physical literature. Citations will be made where appropriate.

There is no literature correlating touch sensations to the rheological parameters of the fluid and skin. In trying to create such a theory, we found that many important features of touch sensations can be framed in terms of lubrication theory, pointing the central role of the bulk viscosity of the lubricant in thick films held apart by hydrodynamic pressures in the fluid and of surface active agents adsorbed on the skin for thin films in the regime of boundary lubrication. We found the ideas of W.B. Hardy [1936] on surface active and inactive films on liquid and metal surfaces to be particularly relevant to touch sensations. Again, citations are given where appropriate.

### **III. The fingers and palms are transducers**

Touch has been defined as the variety of sensations evoked by stimulation of the skin by mechanical, thermal, chemical, or electrical events. The mechanical and physiological characteristics of the skin and the receptor structures define and limit the sensitivity of the skin to stimuli. Below we briefly describe the anatomy and morphology of those structures, both visible and below the surface (see Cholewiak and Collins, 1991).

A schematic section of human skin is shown in figure 1. The surface of the skin is made up of dead or keratinized cell bodies from the deeper subdivisions of the epidermis that have migrated outward as the skin renews itself from the inside out. Immediately below this protective layer is the dermis, a layer of nutritive and connective tissues. Cutaneous end organs, the structure that are responsible for transducing mechanical, thermal, chemical, or electrical energy into neural signals lie within the dermal layer or at the epidermal-dermal interface. Finally, below the dermis there are layers of connective tissue and subcutaneous fat that lie between the skin and the supportive formations of muscle and bone.



**Figure 1.** A schematic section of human skin, showing the locations of cutaneous end organs. This section, through a typical portion of hairy skin, is also representative of glabrous skin with only a few exceptions: There are no hairs in glabrous skin, the overall density of end organs is greater, and the surface of glabrous skin is ridged as a result of dermal intrusions into the epidermis. From *Fundamentals of Neurology*, 5th ed., p.137; E.P. Gardner (Ed.), 1968.

The layers of skin deformed by a stimulus are “viscoelastic.” This means that when the skin is touched, the energy imposed on it at that point will be transmitted through the medium, so it is “viscous.” Some of the energy, however, will be adsorbed and stored, and is used to return the skin to its original state, therefore, the skin is also “elastic.” As energy moves in a wave into the skin, it produces shearing forces that dissipate with distance from the source. The form of the displacement wave changes as it passes through different tissue layers or encounters obstacles. The events that are “witnessed” by the sensory nerve ending within the skin may be quite different from those originally presented at the surface. The location and depth of a cutaneous receptor with the skin can affect how the stimulus acts upon it.

There are several cutaneous end organs (receptors) that are responsible for transducing tactile stimuli into neural signals. Merckel's disk, Ruffini cylinders, and Meissner's corpuscles have all been implicated in the senses of touch and are found in the upper regions of the dermis. Even deeper than these are the Pacinian corpuscles. Figure 1 illustrates the locations of some of these structures in relation to one another.

Units in glabrous skin sensitive to mechanical stimuli have been classified into four groups. The sensory units vary in the size of their receptive fields (large or small) and in how quickly they adapt to a steady stimulus, either fast or slow. Two of the four groups respond to skin indentation only while the stimulus is changing (i.e. transients); they show no response to sustained indentation. Accordingly, they have been described as fast adapting (FA). The other two types do show a sustained discharge during steady indentation of the skin, and have been described as slowly adapting (SA).

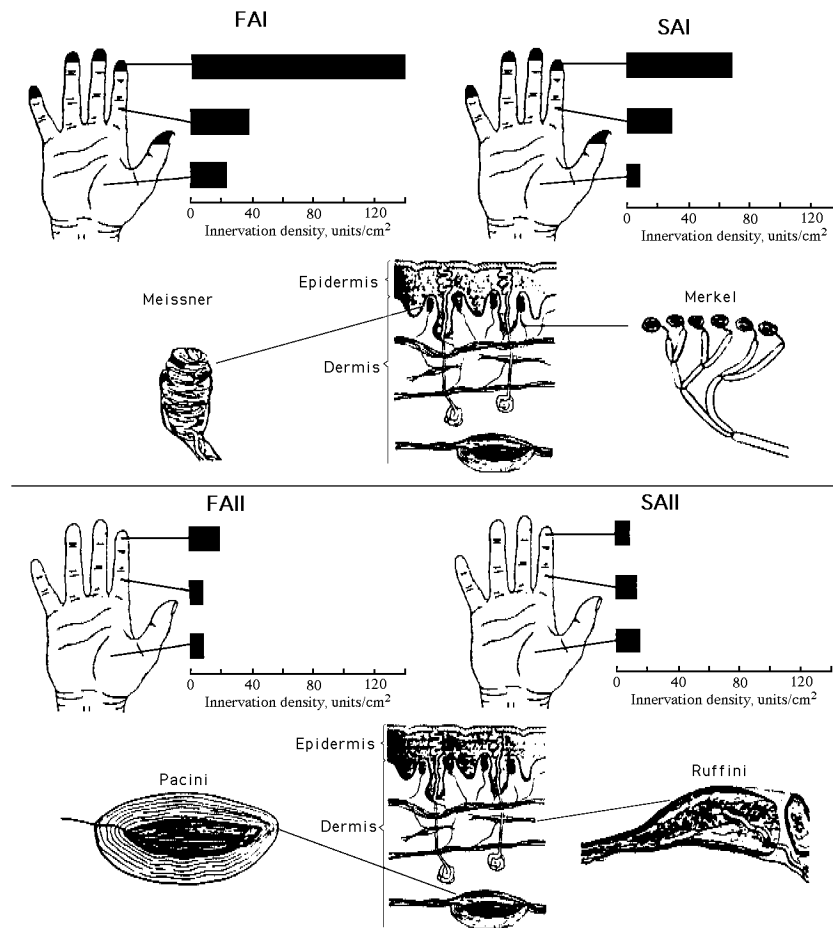
Those fast adapting units with small, distinct receptive fields have been labeled FA I units. It has been suggested that primate FA I units end in Meissner corpuscles found high in the dermal ridges of the skin. It is found that FA I units coded low frequency (5 to 40 Hz) mechanical sinusoids delivered to the hand. It is believed that such units code the human sensation "flutter."

The other fast adapting mechanoreceptors are known as FA II units which have very large receptive fields and code mechanical sinusoids in the range of 40 to 400 Hz. The FA II units have as end organs the Pacinian corpuscles found in subcutaneous tissues.

Of the two kinds of slowly adapting units, the SA I fibers have small, distinct receptive fields, indicating again the potential for coding spatial details. They respond to steady indentation but show low sensitivity to stretch. The end organs of the SA I units are believed to be the Merkel cell complexes, located on the deep aspect of the intermediate ridges (large epidermal folds that project into the dermis).

Finally, the SA II units respond to sustained indentation and have large receptive fields. The fibers are believed to end in Ruffini endings, which are located more deeply within the dermis. SA II units tend to be very sensitive to tangential forces on the skin.

These four mechanoreception units with presumed receptor structures and their density distribution over the surface of the hand are illustrated in figure 2.



**Figure 2.** The gradients of density of FA I, FA II, SA I and SA II units over the surface of the hand are illustrated along with the presumed receptor structures. From "Properties of Cutaneous Mechanoreceptors in Human Hand Related to Touch Sensation", by A.B. Vallbo and R.S. Johansson, 1984. Human Neurobiology, vol.3, pp.3-14.

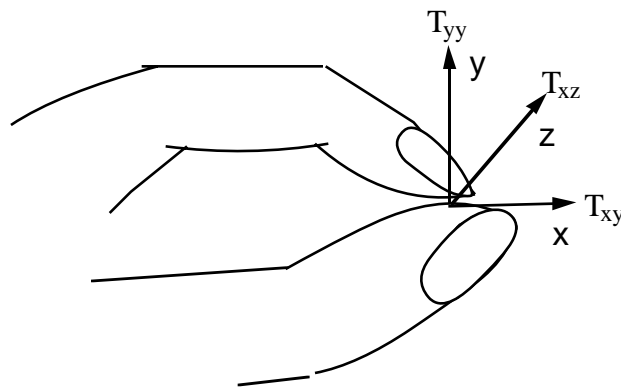
Given the anatomy and physiology of the mechanoreceptors as discussed above, we may think of the fingers and the palm as force transducers which, like mechanical rheometers, can sense shear stress and pressure. Due to the complexity of the sensations subsumed under the general touch conditions, it is likely that all of the mechanoreceptive populations described above will play a role. It is very important to understand touch as a mechanical rheometer because when touch is framed in this way we can correlate sensation with measurement. The nature of such correlations cannot be understood without explanation.

The idea of transducers was introduced by M. M. Taylor, S. J. Lederman and R. H. Gibson "Tactual Perception of Texture" in *Handbook of Perception*, vol. 3, Eds. E. C.

Caterette and M. E. Priesman [1973], pp. 251-272, and a cartoon of a transducer is shown on page 264 of their paper. They correlated the texture perception of a surface with a transducer function and say that “. . . the transducer function that relates the input to the output is determined by the surface texture coupled with the mechanical state of the skin. Provided that the skin state is known, it would not be far wrong to say that the transducer function is the texture. The perception of texture is the analysis of the transducer function. The function contains all the information which can be derived from the mobile contact between the hand and surface.” They did not give any definite result about or use their idea of a transducer function. Their idea is merely presented as a way to thinking.

In the following discussion we shall characterize touch with the fingers with common measures of stress which are measured with commercial rheometers. The difference is that the qualitative experience of sensation replaces the quantitative measuring devices, like pressure and shear stress gages.

In general, the state of stress at a point in a body is determined by six values, three pressures (normal stresses),  $T_{xx}$ ,  $T_{yy}$ ,  $T_{zz}$ , and three shear stresses,  $T_{xy}$ ,  $T_{yz}$ ,  $T_{xz}$ . The stress gives the force per unit area. For touch sensations, we are interested only in, say, the stresses between the fingers (see figure 3). There are only two stresses of relevance in touching:  $T_{yy}$ , which is the pressure of pressing or pulling apart of the fingers, and  $T_{xy}$ , which is the shear stress when touching fingers rub in the tangential direction. We could slide the forefinger in a second direction  $z$  perpendicular to  $x$  and  $y$ . This gives rise to a second shear stress  $T_{xz}$  perpendicular to  $T_{xy}$ . This stress follows the same conditions of touch sensation as  $T_{xy}$  and so will not be considered here.



**Figure 3.** Three stresses, a pressure or tension  $T_{yy}$  and two shear stresses  $T_{xy}$ ,  $T_{xz}$  which are generated by direct and lateral sliding.



## Pressure

We experience pressure  $T_{yy}$  by pressing our fingers together or pulling them apart. This is a static test (involving the slowly adapting mechanoreceptors: SA I and SA II), but we can experience the changes in pressure as we increase the squeezing force between our fingers.

If we put something between our fingers, like a contact lens, and press down, we can judge whether the material between is hard or soft. We can also feel the presence of hard inclusions in a pressure test giving testimony to the idea the differentials in pressures which are induced by differential deformation between places where those are inclusions from those which are not. To a certain extent, we can distinguish shapes in a pressure test.

We experience the sensation of sticky or tacky as a perception of  $T_{yy}$  when we try to pull the fingers apart. This is a tension which can arise only if the fluid between the fingers can support tension as in the case of lens solutions with polymer and/or surfactant additives. We feel a different resistance to separate the fingers for different solutions; for example, more resistance is felt in lens solutions with polymer additives.

## Shear stresses

We can experience static and dynamic shear stress by the lateral motion of our fingers. Static shear stress occurs when fingers are pressed together so strongly that the sliding of one finger over another is suppressed. The fingers will then deform under shear and the shearing deformation can be maintained without sliding. A shearing force is experienced as a sensation in the finger. This static test again involves the slowly adapting receptors in the fingers. However, for dynamic shear stress, the ridges on the surface of the skin on the finger slide over each other creating transient response of the receptors.

The skin–aqueous solution and skin–soft contact lens sensations are directly related to the values of the pressure and shear forces acting on the skin during the touch process. The values of these forces are determined by the dynamics of the motion of the fingers and fluid flow between the skin of the fingers, which are described below.

## **IV. Static and kinetic friction in touch sensation of aqueous films**

We can do some exciting experiments just by sliding the fingers as in figure 3 when different aqueous solutions are between the fingers. Press your thumb and forefinger together.

If they are nominally clean and dry, they feel smooth or slippery. If you press them together hard, you can suppress sliding. If under this pressure  $T_{yy}$ , the sliding force  $T_{xy}$  is increased, at a certain value of  $T_{xy}$  sliding will commence.

There is always a critical value  $\mu = T_{xy}/T_{yy}$  for which sliding commences. This critical value defines a *coefficient of static friction* and it is a very important measure of the slipperiness of aqueous solutions. Static friction, the critical  $T_{xy}$ , is an increasing function of the normal pressure  $T_{yy}$ , as in our finger experiments. When the pressing pressures are small, the force required to slide our fingers is also very small, and when the pressing is very hard, it is very hard to get the fingers to slide.

The ratio of stresses  $T_{xy}/T_{yy}$  during sliding is known as the *coefficient of kinetic friction*. For the same materials, the value of this coefficient of kinetic friction is always smaller than that of the static friction.

Various devices have been employed to measure the coefficients of friction. Usually,  $T_{yy}$  is created by loading with a known weight and  $T_{xy}$  is generated by a tangential force, say, by attaching a thread which passes over a pulley to a pan carrying some other weights. Commercial devices have appeared from time to time. We do not see any easy way to measure the friction coefficient of skin. Perhaps a skin substitute like leather, could be used.

Leonardo da Vinci discovered that the static and low speed dry frictional resistance of ordinary bodies were proportional to their weights and independent of the nominal area of contact. A solid block had the same friction whether sliding on a broad flat face or on a narrow side. He noted that the frictional resistance of polished surfaces have coefficients of friction of 1/4. Amontons [1699] studied dirty surfaces and found the same law with coefficients of friction around 1/3. Coulomb found that the kinetic friction was independent of speed over a short range investigated; the kinetic friction was less than static one; and dry frictional resistance is proportional to the load and is unaffected by the area or speed. This law has come to be known as Amontons law of friction.

When a lubricating film is present, and the rubbing surfaces are well separated, the kinetic frictional resistance is also proportional to the load and is independent of the area and speed. But the load is balanced by the hydrodynamic thrust developed by fluid pressure, and this thrust depends linearly on the viscosity, the speed and area (see Section VI below).

Returning now to the finger experiment, we can establish immediately the profound effects of surface active and inactive films. Wet the thumb and forefinger with saliva. If the gap

between the fingers is thick and pressure  $T_{yy}$  very small, we experience a reduced friction coefficient  $T_{xy}/T_{yy}$ ; the lubrication is in the hydrodynamic regime. But, surprisingly, as we reduce the thickness of the film by rubbing under increased pressure, the friction can increase greatly above what it was under the same circumstances when the fingers are dry. The thinner the film, the greater the friction. The touch sensation comparison between dry and wet films is also notable. The wet film appears to get a certain rigidity giving rise to a feeling of stickiness under sliding, interfering with the lubricating effects of natural skin oils. In fact, if the shearing stress is reduced, the finger will stick at a larger value of static friction.

The same touch sensation can be experienced with tap water between the fingers and also with the contact lens solution Renu®.

A very different touch sensation can be experienced in the same experiment by using a soapy solution, say, small amounts of Palmolive dishwashing liquid solution with water as the working fluid. In this situation, the sensation is greatly enhanced; even when the pressing force  $T_{yy}$  is increased to a large value, slipping is the rule and the critical value  $\mu = T_{xy}/T_{yy}$  for static friction is greatly reduced. There are two remarkable features to this experiment. The slipperiness persists even in the thinnest films; it is very difficult to rid the fingers of slipperiness except by washing, though the restoration of “dry” friction is easily obtained by repeated rubbing and evaporation. The second remarkable feature is that the enhanced slipperiness does not depend strongly on the amount of soap in solution. Small quantities of the soap in the water produce as much enhanced slipperiness as large quantities. We shall argue that this is an effect of preferential adsorption of surfactant on the skin.

Similar sensations are felt when a contact lens, or even a paper sheet is placed between the fingers. The same experiment can be carried out when there is a layer of fluid between the fingers, or between the fingers and the lens, and different aqueous solutions may be tested in this way. The increase of friction induced by water films is used everyday. To count a stack of dollar bills or to turn the pages of a book, we moisten our fingers, but they should not be moistened with a soapy solution.

## **V. Lubrication theory**

We found the best guide to a theory of the rheology of touch sensation in the theory of lubrication. Evidently, the rubbing of the fingers in the presence of an aqueous solution or between the finger and the lens is a realization of one or the other of the regimes of lubrication

except that the surfaces to be lubricated are not metal, and they deform readily. In the most general form of lubrication theory, any kind of surface could be considered, so that our touch sensation problem can be regarded also as a chapter in lubrication theory.

There are three basic regimes of lubrication. At one extreme is hydrodynamic lubrication, where the rubbing surfaces are well separated by a thick lubricating film (say, thickness greater than  $2.5\mu\text{m}$ ) and the load imposed on the surfaces is fully borne by hydrodynamic pressure formed in the film. In this regime the coefficient of friction is small and depends on no other material property of the lubricant than its bulk viscosity. At the other extreme is boundary lubrication, where the lubricating film is so thin (from  $1\mu\text{m}$  down to molecular thickness) that its properties are no longer the same as those of the bulk, and load is mostly borne by direct contact between the surfaces by the touching asperities. In this regime small amounts of surface active materials in the lubricant become very important since they may form a suitable molecular layer of lubricant on the touching asperities and greatly reduce the friction between sliding surfaces. Between these two extremes, there is a thin film regime of mixed hydrodynamic – boundary lubrication where the touching of asperities is not important and the load carrying capacity is shared by the surfaces and the fluid. In this regime, the coefficient of friction depends on surface roughness (texture) and on the active or inactive nature of the lubricant with the surfaces.

All of the regimes of lubrication can be experienced in experiments on touch sensation using aqueous solutions. The regime of hydrodynamic lubrication is the best understood of the three regimes. It occurs only when the gap between rubbing surfaces is flooded. We shall see that in this case, the fingers cannot sense each other and all touch sensations depend on the bulk properties of the fluid alone. The gap between sliding fingers will be held open by the hydrodynamic pressure in the fluid film more easily when the fluid viscosity is large, and the viscosity is the most important bulk property for this regime. The lubricant gives rise to slippery sensations in the hydrodynamic case and different fluids with the same viscosity feel the same when the sliding velocity is the same. Glycerin increases slipperiness when the surfaces are heavily flooded due to the opening action of the high viscosity, but a thin film of glycerin feels much like water and does not increase slipperiness in the regime of boundary lubrication.

Boundary and mixed lubrications are less well understood than hydrodynamic lubrication, but are even more important for the understanding of touch sensation. In the touch sensation, since the skin of the fingers can readily deform, there may be no distinction between the regimes of boundary lubrication and thin-film mixed lubrication. Below we just refer these two regimes as boundary lubrication.

Excellent books on boundary and hydrodynamic lubrication are by Hersey [1966] and Bowden and Tabor [1964, 1986]. An excellent modern discussion and critique of Hardy's theory can be found in Adamson [1976].

## **VI. Hydrodynamic lubrication**

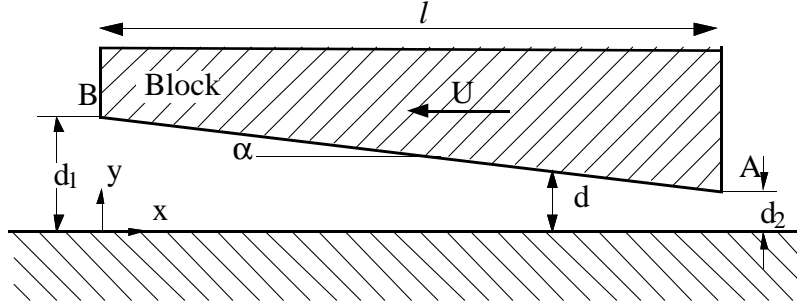
The rheology of aqueous solutions used for contact lenses can be complicated by the addition of polymers, surfactants and small particles. However, in rubbing or shearing motions between fingers or between finger and lens, and in all wet shearing motions, the most important bulk parameter is the viscosity, and the viscosity of water is the only bulk material parameter which can enter when no additives are present.

We may inquire what are the main effects of viscosity in hydrodynamic lubrication? In general, the viscosity is the constant of proportionality between the shear stress and strain rate. Hence, viscosity only enters when the strain is changing, when the fingers are in tangential motion relative to one another. The more viscous the fluid, the greater is the lateral force required to move the fingers laterally. However, it is not likely that the viscosity of aqueous solutions used for contact lenses is that different, even with additives. Hence, the resistance to shearing is one of the main effects of viscosity in wet lubrication.

Another main effect of viscosity in wet lubrication is to provide the dynamically generated pressure in the lubricant which keeps the gap open when they are pressed together. This is an important mathematical statement which needs to be carefully explained and then interpreted.

We may model the sliding motion between lubricated fingers or between the finger and lens as a slipper bearing, see figure 4. We will now present this well known theory and try to interpret it for application to wet lubrication with aqueous solutions. Our model is oversimplified and can be greatly improved at the cost of doing a more complicated mathematical model which is more difficult to interpret.

In figure 4, the block is supported by pressure which is developed when the lubricating solution is dragged through the gap. We may imagine that the bottom plane which is stationary is the palm of the hand, the lubricant is an aqueous solution and block is the moving finger which is pressed against the palm but is held away by the pressure which is developed in the gap.



**Figure 4.** The lubrication layer between two plane layers.

In our model, we are going to solve a simplified form of the Navier-Stokes equations

$$\frac{d^2u}{dy^2} = -\frac{G}{\mu} \quad (1)$$

and suppose that flow takes place between the planes at  $y=0$  and  $y=d$ . In (1),  $G$  is the applied pressure gradient and  $\mu$  is the viscosity of the lubricant. If the plane at  $x=0$  is stationary and the block at  $y=d(x)$  is moving with the velocity  $-U$  as in figure 4, then

$$u = \frac{G}{2\mu}y(d-y) + U\frac{d-y}{d} \quad (2)$$

The simplified (1) is valid when  $d$  is small and the Reynolds number is small

$$\frac{\rho Ud}{\mu} \ll 1 \quad (3)$$

where  $\rho$  is the density of the fluid.

The volume flux, per unit width of the fluid layer, is

$$Q = \int_0^d u dy = \frac{Gd^3}{12\mu} + \frac{1}{2}Ud \quad (4)$$

and  $Q$  must be independent of  $x$ . This requires the pressure gradient to vary with  $d$  according to the relation

$$\frac{dp}{dx} = -G = 6\mu\left(\frac{U}{d^2} - \frac{2Q}{d^3}\right) \quad (5)$$

in which  $d = d_1 - \alpha x$  . Integration of (5) gives

$$p - p_0 = \frac{6\mu}{\alpha} \left\{ U \left( \frac{1}{d} - \frac{1}{d_1} \right) - Q \left( \frac{1}{d^2} - \frac{1}{d_1^2} \right) \right\} \quad (6)$$

where  $p_0$  is the pressure at  $x = 0$  and  $d = d_1$ . Now the sliding block may be supposed to be completely immersed in the fluid, with narrow passages for the fluid on one side of the block only, so that the pressure at the two end points  $A$  and  $B$  are approximately the same. This condition, that  $p = p_0$  when  $d = d_2$ , enables us to determine  $Q$  from (6):

$$Q = U \frac{d_1 d_2}{d_1 + d_2} \quad (7)$$

and then the expression for the pressure becomes

$$p - p_0 = \frac{6\mu U}{\alpha} \frac{(d_1 - d)(d - d_2)}{d^2(d_1 + d_2)} \quad (8)$$

The volume flux and the pressure distribution in the lubrication layer can now be calculated when the sliding velocity  $U$  and the inclination of the sliding block are known. The pressure increment  $p - p_0$  is one-signed throughout the layer, and is positive only when  $d_2 < d_1$ , as anticipated in figure 4. Thus a lubrication layer will generate a positive pressure, and will be able to support a load normal to the layer, only when the layer is so arranged that the relative motion of the two surfaces tends to drag fluid (by viscous stresses) from the wider to the narrower end of the layer. The pressure increment has a single maximum in the layer, and its value there is of order  $\mu U / d_1^2$  (assuming  $(d_1 - d_2) / d_1$  to be of order unity), showing that very high pressures can be set up in very thin films.

The total normal force exerted on either of the two boundaries by the fluid layer is

$$\int_0^l (p - p_0) dx = \frac{6\mu U}{\alpha^2} \left\{ \log \frac{d_1}{d_2} - 2 \left( \frac{d_1 - d_2}{d_1 + d_2} \right) \right\} \quad (9)$$

The total tangential force exerted by the fluid on the lower plane is

$$\int_0^l \mu \left( \frac{\partial u}{\partial y} \right)_{y=0} dx = \frac{2\mu U}{\alpha} \left\{ 3 \left( \frac{d_1 - d_2}{d_1 + d_2} \right) - 2 \log \frac{d_1}{d_2} \right\}$$

and the tangential force on the upper boundary is

$$-\int_0^l \mu \left( \frac{\partial u}{\partial y} \right)_{y=d} dx = \frac{2\mu U}{\alpha} \left\{ 3 \left( \frac{d_1 - d_2}{d_1 + d_2} \right) - \log \frac{d_1}{d_2} \right\}$$

the two tangential forces are not equal and opposite because the normal force on one plane has a (small) component parallel to the other plane. Thus the ratio of the tangential to the normal forces acting on the block defines the coefficient of friction:

$$\frac{\text{tangential force on block}}{\text{normal force on block}} = \alpha \times \text{function} \left( \frac{d_1}{d_2} \right) \quad (10)$$

and, if  $(d_1 - d_2)/d_1$  is of order unity, the order of magnitude of this coefficient of friction is  $d_1/l$ . Somewhat surprisingly, the ratio of the two components of force is independent of the viscosity of the fluid, and can be made indefinitely small by reduction of  $d_1$  with  $d_1/d_2$  held constant.

Now we do some interpretations of the solution just presented in terms finger motions on the lubricated palm. The total normal force (9) can be regarded as force at which the finger is pushed to the palm. This force increases with the viscosity  $\mu$  and velocity  $U$ . According to this solution, it would take an infinite force to close the gap, as  $d_2 \rightarrow 0$ . The tangential force also becomes logarithmically infinite as  $d_2 \rightarrow 0$ . This is paradox which is resolved by noting that  $d_2 \rightarrow 0$  the flow regime changes from hydrodynamic to boundary lubrication and elastic forces from contacting skin-palm asperities become important.

Equation (9) shows that the gap size  $d_2$  will be larger when the viscosity is larger, if the normal force and other parameters are fixed. We interpret this to mean that we can hold the gap open and avoid mixed lubrication by increasing the viscosity of the lubricant. The result (10) shows that the effects of viscosity are actually more important in holding the gap open than in resisting tangential motion. We can also keep the gap open at a given rubbing speed by reducing the pressing pressure between the palm and hand.

As we have seen that high pressure can be set up in very thin films. Due to this pressure, the ‘‘viscoelastic’’ skin on the fingers will deform, and the actual shape of the gap will change accordingly. The analysis presented above will not be valid for the practical situations. However, we think that the only fluid parameter affecting the shear force on the surface which generates



touch sensation is its bulk viscosity. Thus, in the regime of hydrodynamic lubrication, one only needs to measure the viscosity of the fluid.

We measured the viscosities of the four contact lens solutions, Bausch & Lomb Renu<sup>®</sup>, Allergan Refresh Plus<sup>®</sup>, Allergan Complete<sup>™</sup> and Alcon Opti-Free<sup>®</sup>. The viscosities of Bausch & Lomb Renu<sup>®</sup>, Allergan Complete<sup>™</sup> and Alcon Opti-Free<sup>®</sup> are very close to that of water, 1 centipoise. However, the viscosity of Allergan Refresh Plus<sup>®</sup> is about three times that of the water, which gives rise to a different sensation, slipperiness, when the surfaces are heavily flooded due to the opening action of the high viscosity.

## **VII. Boundary lubrication**

The subject of thin-film and boundary lubrication is an old one motivated by the observation that bearings which are lubricated with, say, a mineral oil containing small amounts of fatty acids, run with much less friction, even when they are starved of lubricant. This lubrication, which can be measured by the coefficient of static friction cannot depend on the viscosity, since viscosity does not affect the static friction. Moreover, it was found that a mineral oil containing only a small percentage of fatty acid lowers the friction almost as much as a straight fatty acid. This can be explained by the preferential adsorption of fatty acids on the metal surfaces of the bearing and the adsorbed fatty acids lower the static friction coefficient.

The foregoing mechanism of selective adsorption of surface active agents reduces friction greatly between rubbing fingers lubricated by various soapy solutions, even when the percentage of soap in solution is very small.

It is generally understood that the action of fatty acids in reducing friction is due to the molecular adherence. The fatty acid adheres to the surface with sufficient strength to resist being torn off when rubbing surfaces slide over each other. It has been shown that the molecules of fatty acids have carboxyl groups (the active end of the molecule) that attach themselves to the metal surface. Ordinary mineral oils do not have this polar group. The fatty acid molecules orient themselves with the carboxyl groups at the solid surface. This results in the formation on the surface of a film of fatty acid molecules all standing up from the surface, much like a pile of a carpet (figure 5). The forces of adhesion are sufficiently strong to resist removal of the fatty acid molecules. The layers of molecules actually isolate the surface forces of the two metals, and the friction which would be high in the absence of a lubricant, is substantially reduced. Actually there is no reason to assume that the orientation of the molecules of the lubricant is limited to the layer adjacent to the metal. In general, fatty acids array themselves so that several layers of

molecules will be oriented. This orientation gradually disappears in the layers farther away from the surface.

The bond between the active end of the fatty acid molecule (the polar or carboxyl end) and the solid surface is a very tenacious one. There are indications that show a chemical reaction actually taking place. This reaction produces a soap film that is chemically bound to the metal surface. There are suggestions that, under conditions of sliding, lubrication is effected not by the fatty acid itself but by the metallic soap formed as a result of chemical reaction between the metal and fatty acids.

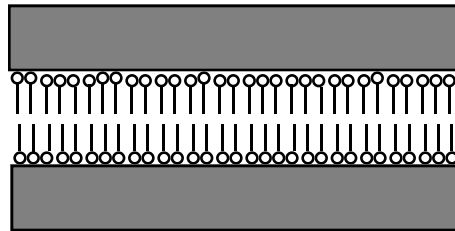
In the boundary lubrication regime, the variables affecting or not affecting the friction force are briefly summarized below:

- a. The friction force is directly proportional to the load.
- b. The friction force is independent of the gross area of the contacting surfaces.
- c. The friction force depends upon the material properties of the sliding surfaces.
- d. The friction force is independent of the sliding velocity within certain limits.
- e. The friction force is influenced by other variables such as temperature, surface roughness, vibration and the like.
- f. The friction force depends upon the chemical composition of the lubricant and/or the product of reaction between the lubricant and the solid surface.
- g. The friction force is independent of the bulk viscosity of the lubricant.

The theory of boundary lubrication may be developed further by considering the properties of "composite surfaces." When a substance, say, an oil, spreads on water, under the influence of surface forces, a surface is formed whose properties are neither those of a clean surface of water nor of the oil. The water and the oil have in fact reacted on one another. Such surfaces may be called "composite." All naturally occurring surfaces are composite because the free energy of such a composite surface is less than that of a clean or simple surface. The reaction between the components of a composite surface can be classified as chemical, but in a very restricted sense because the condition of immiscibility of the components makes the relation of the molecules two-dimensional. The thermodynamics of systems in equilibrium teaches that surfaces tend spontaneously to assume a condition of minimum free surface energy. At an interface between a metal and a mineral oil containing fatty acids in solution, the constituent of the solution which lowers the interfacial tension by the greater amount should, therefore, become more concentrated than in the solution as a whole. Because of this principle, the fatty acids must reduce the surface tension of metals more than mineral oil.

The same principle holds at fluid interfaces. Experiments cited by Bukley and Snyder [1933] have presented data showing that the interfacial tension between mercury and fatty liquids is considerably lower than between mercury and hydrocarbons or mineral oils. The differences reported are of the order of 20 to 50 dynes per cm. It is also shown that the addition of small percentages of fatty acid to a mineral oil progressively lowers interfacial tension between oil and mercury.

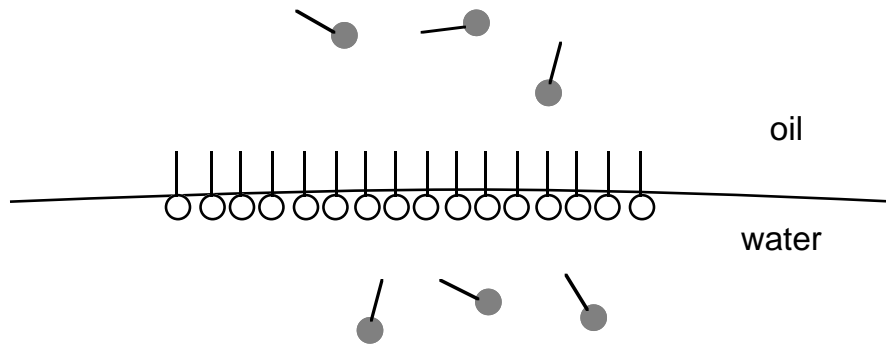
The partial nature of the reactions and the structure of a composite surface may be illustrated by example. When an aliphatic acid such as palmitic acid forms a film on water, the film is probably only one molecule thick and the carboxyl groups are attracted by the water so that each molecule stands on end. The film, therefore, is composed of a layer of carbon chains oriented at right angles to the water surface. Orientation to an unknown degree may also be obtained in the superficial layer of the water itself (figure 5).



**Figure 5.** Contact region in boundary lubrication according to Hardy [1936]. He showed that boundary lubrication could be explained in terms of adsorbed films of lubricants and proposed that the hydrocarbon surfaces of such films reduced the fields of force between the two parts. The most active films are of polarizable molecules stretching through the lubricant from one enclosing solid to another. Each chain has little strength in shear, great strength in tension and in both the strength weakens as the chain lengthens. Surprisingly, this description works well for “soapy” film on the skin, or between the skin and a contact lens.

Composite surfaces are formed on solids in a way so similar to that obtained on fluids as to make it practically certain that they have the same general structure, namely marked orientation of the molecules (figure 6).

Consider two such composite faces applied to one another; the orientation may be disturbed by mutual attraction between the molecules in the films but it will not be destroyed. The applied faces now form a region which varies rapidly in constitution along the normal direction to the interface, and its boundaries are indefinite, for we do not know how far into the liquids or solids the molecular pattern characteristic of the region extends.



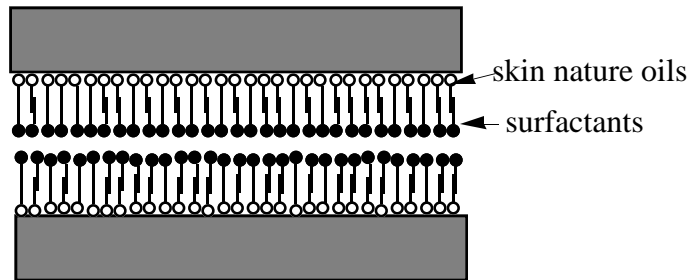
**Figure 6.** Adsorption of surface active agents (surfactants) on oil-water surface. The surfactant has a head which likes water and a hydrophobic tail. The surfactant is attracted to the interface where they can be comfortable. The saturated surface is uniform along the interface with sharp changes across.

Hardy and Hardy [1919] discussed surface active and inactive fluids. Surface active fluids are those which facilitate slipping on surfaces in layers of any thickness; they facilitate slipping in the layer of insensible thickness as well as in layers of the order of one micron. Fatty acids facilitate slipping. On the hand, inactive fluids are lubricants which have little or no power of altering the solid surfaces as to facilitate slipping. Water, ethyl ether and ethyl alcohol, for example, are inactive fluids. The thickness of films formed on solid surfaces has not yet been directly measured, but analogy justifies us in assuming that if the area is large enough, the film will be one molecule thick and that it can be thickened by contracting the area in reference to the quantity of foreign substance present in it. The relation of the friction to the thickness of film on each solid face is difficult to follow, but the evidence so far available points to the conclusion that static friction decreases as the layer of the lubricant is increased, but rapidly reaches a minimum when it begins to increase until the critical thickness of the film is reached beyond which flotation occurs. At the critical thickness, static friction falls more or less abruptly to zero.

It is remarkable that the foregoing features of boundary or thin-film lubrication apply so well to touch sensations in aqueous solutions. We already noted that rubbing friction on “dry” fingers is much smaller than when the fingers are lubricated with an inactive thin fluid film, say a water layer. The reason is that the fingers are never dry and clean but are covered by skin oils (active fluids) which lubricate the fingers. The addition of an inactive water layer reduces the effect of an active fluid (skin oils) possibly by changing the force fields between the fingers, with greater short range effects for thinner layers of water. There is much of scientific interest in the way the water acts. It does not remove or even temporarily detach the film of lubricant, for the full influence of the latter is restored when the water is dried off. On the other hand, it would seem to lessen the grip of the oil film on the skin surface, for the later can be detached by lightly rubbing the surface under the water. This phenomena is the same as the well known fact that a

few drops of water wetting the parts in contact will prevent a cup of tea from slipping about a saucer.

When an active fluid, say a soapy solution, is used, a more slipperiness sensation can be experienced. One mechanism of the action of an active fluid on the surface of the skin covered with skin oils is related to the direct adsorption of the surfactants in the soapy solution onto the oily skin surface, as shown in figure 7. The newly formed surfactant film lowers the energy of the surface even more, giving rise to the reduced friction between the rubbing fingers and the sensation of more slipperiness.



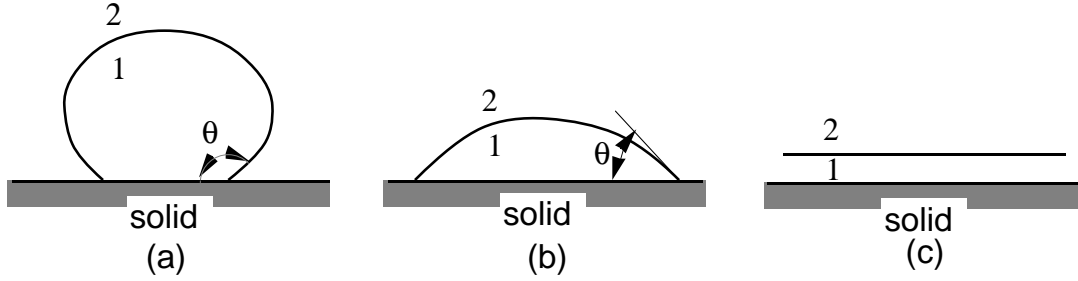
**Figure 7.** Adsorption of surfactants on the oily skin surface.

The other possible mechanism for the action of an active fluid on the surface of the skin covered with skin oils is related to the wetting and spreading phenomenon. We shall explain in the next section that this is an effect of preferential adsorption of surfactant on the skin.

The existence of surface active and inactive fluids also carried over to touch sensations as do other properties; for example, surface active agents like soaps work as well in small as in large concentrations in water. No work has been published on the classification of surface active and inactive agents in touch sensations, though it is probable that soap and shampoo companies have considerable information about surface active agents which reduce friction.

### **VIII. Wetting, spreading and adsorption**

The concepts of wetting, spreading and adsorption, especially adsorption, are fundamental to an understanding of boundary lubrication and touch sensation. The thermodynamic wettability of solid surfaces was clarified by Zisman [1964] but the deviations from thermodynamic equilibrium are only beginning to be understood (de Gennes [1985]). It is necessary to distinguish between partial wetting and complete wetting as shown in figure 6.



**Figure 8.** A small droplet over a horizontal solid surface.  $\theta$  is the contact angle. There are two immiscible fluids: 1 and 2. The fluid 2 can be a gas or vapor and is considered in thermodynamic equilibrium. (a) and (b) correspond to partial wetting, the trend being stronger in (b) than in (a). (c) corresponds to complete spreading.

The wetted portion of the solid in figure 8 is delimited by a contact line. Obviously, the whole solid is wetted in (c). It is easiest to understand by considering “dry” solids when fluid 2 is the vapor of fluid 1. Then according to Young’s equation,

$$\gamma_{s2} - \gamma_{s1} - \gamma \cos \theta = 0 \quad (11)$$

where  $\gamma$  is the interfacial tension between fluids 1 and 2.  $\gamma_{s2}$  is the energy per unit area of the portion of the solid wetted by fluid 2, and  $\gamma_{s1}$  is the same relative to fluid 1. There are many ways to measure  $\gamma$  and it can be considered known. When the contact angle  $\theta$  is zero or so close to zero that the liquid spreads over the solid easily, the fluid 2 is said to be wetting. On the other hand when the angle is greater than  $90^\circ$  so that liquid tends to ball up and run off the surface easily, it is said to be nonwetting.

In equilibrium, (11) shows that

$$\gamma_{s2} - \gamma_{s1} \geq 0, \quad 0 \leq \theta \leq 180^\circ$$

When you put a fresh drop of fluid 1 on a surface, it will expand to some equilibrium value, generally not to the ideal equilibrium value. The drop is said to *spread*. Spreading occurs in nonequilibrium situations, by definition.

If the surface energies  $\gamma_{s2}$  and  $\gamma_{s1}$  are small and  $\gamma$  is fixed, the contact angle  $\theta$  is very small. To understand spreading, put  $\theta = 0$ ; then  $\gamma_{s2} - \gamma - \gamma_{s1} = 0$ . We can distinguish between spreading onto a “dry” surface and spreading onto a “wet” surface. The wet surface is one which is covered with an adsorbed film, the usual situation. For the “dry” case, we define a “spreading” coefficient

$$S = \gamma_{s2} - \gamma - \gamma_{s1} \quad (12)$$

which can be much greater than zero. The case  $S > 0$  occurs when an adsorbed film is spreading. Qualitatively speaking,  $\gamma_{s1}$  and  $\gamma$  should be made as small as possible if spreading is to occur. From a practical viewpoint, this is best done by adding to the liquid phase a surfactant that is adsorbed at both the solid-liquid and the liquid-air interfaces and therefore lowers these interfacial tensions. If the surfactant is nonvolatile, it is presumed not to affect  $\gamma_{s2}$ .

The subject of spreading and adsorption is best introduced with examples. White mineral oil which will spread indefinitely on clean glass in an atmosphere at 40% humidity, but if placed on the same surface in an atmosphere at 70% humidity, it will stop spreading after a few minutes. If the humidity is initially low and the drop is allowed to spread until it is considerably greater than its equilibrium size at 70% humidity, and the humidity then raised to 70%, the drop will retract to the equilibrium size. Acetic acid, on the other hand, shows exactly opposite behavior. It acts as a non-spreading liquid in a perfectly dry atmosphere, but spreads rapidly if a small amount of moisture is admitted to the atmosphere.

Bukley and Snyder [1933] describe some experiments which illuminate the nature and consequences of adsorption of surface active substances onto “dry” surfaces. When a drop of oleic acid is placed on a clear polished surface of steel, it apparently does not wet the plate at all, but can be rolled about in much the same manner as a drop of mercury. A film of mineral oil spreading on the plate is halted abruptly at the invisible path along which the oleic acid has passed, thus giving evidence of the deposition of an exceedingly thin film on that part of the plate with which the drop has been in contact.

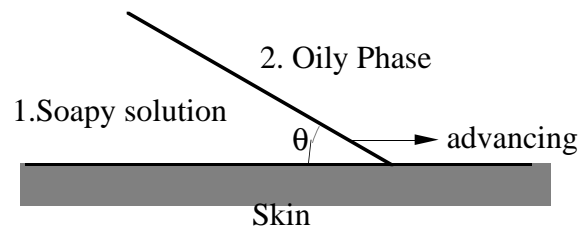
Mineral oils which spread rapidly on ordinary metal surfaces seem to have no spreading tendency when placed on a metal surface which is covered with the invisible fatty acid film. The drop of fatty acid leaves behind it an adsorbed film of only a few molecules thickness.

The effect of the adsorbed film in reducing the wettability of the metal surface by mineral oils goes further. This was demonstrated by rolling several drops of fatty acid across a plate, and then dipping the lower half of the plate into a beaker of mineral oil. When the plate was withdrawn, the clean metal retained a relatively thick layer of oil for an indefinite period, but all the oil ran off those portions which the fatty acid drops had touched. When a drop of thin mineral oil containing 1 or 2% of oleic acid was placed on a polished steel plate, it spread rapidly outward for a few minutes, at which time a hole appeared in the layer near its edge. This hole became elongated, expanding parallel to the circumference of the spreading layer. The main

body of the oil pulled inward as the rupture progressed, until at last the oil was completely separated into two portions: a surrounding ring which continued to expand outward at a more rapid rate than the ordinary spreading, and an inner pool which contracted to a relatively small radius and then remained dormant. On the metal surface between these two portions, no liquid was visible. The surface was found to be covered with an adsorbed film similar to the one obtained from the pure acid.

The spreading of oleic acid onto clean steel is associated with a large nonequilibrium value of  $S$  and  $\gamma_{s2}$  in (11), and leads to adsorption. The adsorption of the oleic acid reduces the surface energy of the solid without changing the value of the tension  $\gamma$ . Now the solid under the drop and on the formerly dry steel have the same adsorbed layer so that  $\gamma_{s2} - \gamma_{s1}$  in (11) is small; hence,  $\cos\theta$  is small and we have a finite contact angle  $\theta$  perhaps closer to  $90^\circ$  than to zero and the drop of mineral oil will contract. We get a drop of mineral oil on a solid surface covered with a molecular layer of oleic acid. Of course the ring of mineral oil with fatty acid will continue to propagate outward onto the dry surface.

The preferential adsorption of surfactant on the skin may be used to explain the more slipperiness sensation experienced when a soapy solution is between the rubbing fingers. We have already mentioned that the "dry" fingers are covered by skin oils, denoting as fluid 2. The soapy solution, acting as fluid 1, will displace the oil film on the surface of the skin when the spreading coefficient  $S$  defined in (12) for the soapy solution phase is greater than zero, indicated in the situation of figure 9. This is the rolling-up mechanism for the removal of oily soil from fiber surfaces in the detergent action. In order to make the adhesion of the oily phase to skin zero or negative, it is desirable to decrease  $\gamma$  and  $\gamma_{s1}$  as much as possible, with a minimum of change in  $\gamma_{s2}$ . By this reasoning, a surfactant that adsorbs both at the oil-water and at the skin-water interface should be effective. The surfactant film formed at the surface of the skin is more active than the original skin oils, since it lowers the energy of the surface more, giving rise to the reduced friction between the rubbing fingers and the sensation of more slipperiness.



**Figure 9.** Surface tensional relationships in oily phase removal.



## **IX. Friction, wetting and spreading in touch sensation**

### *Friction*

We did experiments with several well-known surfactants used to reduce interfacial tension at liquid-liquid surfaces. These surfactants have hydrophilic heads and hydrophobic tails (see figure 6) and are classified in terms of the polarity of the hydrophilic head: anionic surfactants have a negative polarity, cationic surfactants have positive polarity and nonionic surfactants are not polar. Carboxylic acids, sulphuric acids and sulfonates are anionic, fatty nitrates and amines are cationic and polyetonoxy and polyhydroxy surfactants are nonionic.

Touch sensation can be profoundly altered by the presence of small amounts of surface active agents. We find strong differences in the static and rubbing friction between fingers lubricated by aqueous solutions with small amounts of surfactant. In particular, small amounts of sodium dodecyl sulphate (SDS-5%), an anionic surfactant, reduced friction greatly, even in small amounts, less than 5%. On the other hand, another nonionic surfactant, TRITON (X100-5%), which was described in Section VII as inactive, gives rise to a water-like lubricating layer. Perhaps the carboymethylcellulose used in REFRESH PLUS<sup>®</sup> is an anionic surfactant like SDS.

The results of our studies of touch sensation of rubbing friction between the thumb and forefinger (figure 3) are summarized in Table 1. All of the inactive fluids behave like water. The friction between the fingers has a maximum when the water layer is very thin with smaller friction for flooded fingers and “dry” fingers. We have also noticed the sensation of tackiness when one tries to separate the fingers after the lubricating layer has been reduced to a small size by rubbing.

The reader can find the four contact lens solutions, Bausch & Lomb Renu<sup>®</sup>, Allergan Refresh Plus<sup>®</sup>, Allergan Complete<sup>™</sup> and Alcon Opti-Free<sup>®</sup> in Table 1. Of these, Refresh Plus<sup>®</sup> is the most active, giving rise to slipperiness and tackiness. On the other hand, Allergan Complete<sup>™</sup> gives rise to greater friction than the others, possibly due to the presence of particles.

<b>Fluid</b>	<b>Description of Frictional Characteristics</b>	<b>Description of Adhesive Characteristics</b>
Distilled water	Minimal lubrication in a thick film, but as pressure increases, so does friction, until it exceeds the case for dry fingers.	No tackiness.
Alcon Opti-Free®	Minimal to no lubrication in both the thick and thin film case. Very similar to water.	Minimal tackiness.
Allergan Complete™	Some lubrication in the thick film, but much more noticeable in the thin film and very persistent with continuous rubbing of fingers.	Some tackiness, though much less noticeable than other fluids, like SDS or glycerin.
Allergan Refresh Plus™	Very similar to Complete™	Some tackiness.
Bausch & Lomb Renu®	No lubricative qualities. Very similar to water.	Minimal tackiness.
Soybean oil	Substantially slippery in both the thin and thick film cases.	Very tacky (i.e. resistant to separation of fingers.)
1 wt% SDS	Somewhat slippery, but friction significantly increases when gap reduces to thin film.	Somewhat tacky (i.e. more so than contact lens solutions, but not nearly as much as soybean oil.)
5 wt% SDS	More slippery than 1 wt% SDS in both the thick and thin film cases.	Somewhat tacky (same as above.)
10 wt% SDS	Much greater lubrication than lesser concentrations. Very persistent in the thin film.	More so tacky than lesser concentrations
15 wt% SDS	Extremely slippery in both the thick and thin film.	Similar to 10 wt%, but still much less tacky than soybean oil or glycerin.
0.2 wt% Triton X-100	Very similar to water due to low surfactant concentration.	No tackiness.
0.5 wt% Polyacrylamide	Extremely slippery in both the thick and thin film, more so than any other fluid.	Very tacky (more so than SDS but less than soybean oil and glycerin.)
100 ppm Polyox	Very similar to water.	Minimal tackiness.
500 ppm Polyox	Some lubrication in the thick film, but friction sharply increases in the thin film.	Very tacky (similar to 0.5 wt% Polyacrylamide.)
99.9 wt% Glycerin	Very slippery in the thick and thin film. Very comparable to the higher concentrations of SDS.	Extremely tacky (most substantial of all fluids tested.)

(NOTE: All solutions in distilled water.)

**Table 1.** Psycho-physical descriptions of the frictional and adhesive characteristics of the fluids.

### Wetting and spreading

We did experiments on the wetting of the skin with many of the aqueous solutions mentioned in Table 1. A 0.1 ml drop was placed on the touching part of the third finger from the thumb and the drop was photographed immediately after formation. Drops of water and contact lens solutions do not wet the skin strongly, but surfactants, both anionic and nonionic, promote the wetting by aqueous solutions. The photographs show that oil does wet the skin more than aqueous solutions because dry skin is already oily.

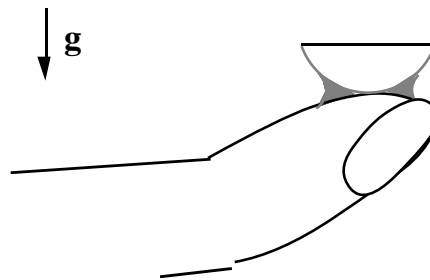
We did not find any obvious connection between wettability and rubbing friction. Rubbing friction does not depend on interfacial tension of the liquid and air and wettability does not depend on the internal structure of the lubricating layer in adsorption dominated regime of

boundary lubrication. SDS and TRITON have about the same effect increasing wetting but greatly different effects reducing friction.

### Contact lens

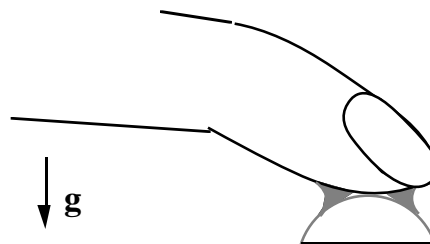
Soft lens are hydrophilic; aqueous solutions spread completely and permanent non-zero contact angles are not possible. We did not study adsorption of surface active agents on contact lenses, but it is a subject of interest.

In placing a contact lens in the eye, one sticks the convex side of the lens on the wetted finger, where it is held against the finger by capillarity.



**Figure 10.** Lens held on the finger by capillarity of the lens solution.

The soft lens is so weak that it flattens against the finger by capillary of the liquid bridge between the finger and the lens. You can turn the finger upside down, but will not pull the lens off.



**Figure 11.** The lens won't fall off under gravity.

The lens solution pulls the lens to the finger and it is balanced by bending stresses in the lens. The strength of the attachment of the lens to the finger is of interest for the transfer of the lens from the finger to the eye and for the removal of the lens. These features of lens transfer give rise to touch which we did not study. The properties that are relevant here are:

1. Wettability of the skin;
2. Surface tension;

3. Bending strength of the lens; and
4. Tackiness of the lens solution.

For transfer, we would imagine that tackiness would be unpleasant, but the bond between the lens and finger should not be too weak.

### **Acknowledgment**

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## **Identification and Description of Tools to Accurately Measure the Physical Components**

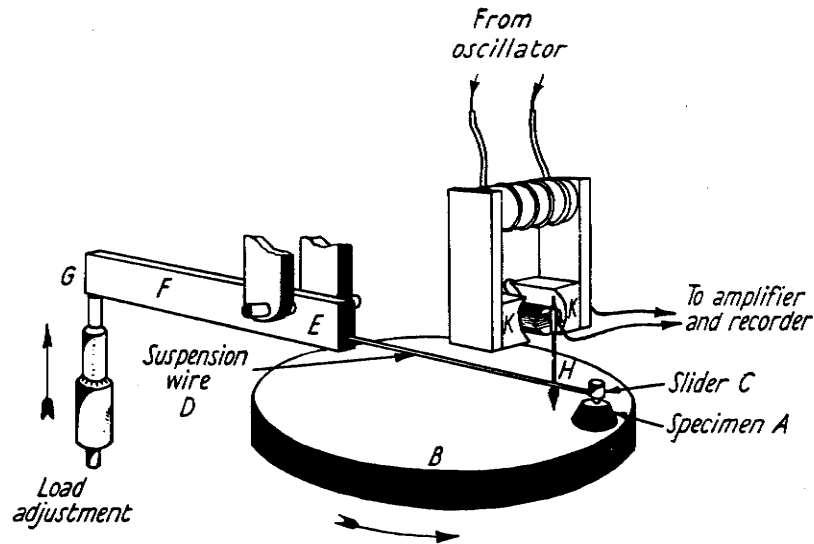
We have noted that touch sensation arises from the neural signals of the nerve ending receptors beneath the surface of the skin in response to the two forces acting on the surface of the skin: the pressure force normal to the touching surface and shear force tangent to the surface. The normal force between the fingers and palms, separated by an aqueous solution, is experienced as pressure when the fingers are pressed together or as tacky or sticky when the fingers are pulled apart. The shear force gives rise to the sensation of slipperiness or friction when the fingers are rubbed against each other.

The experiences of stickiness and slipperiness depend strongly on the thickness of the liquid film between the sliding fingers. For thick films, the sensation can be solely characterized by the bulk viscosity of the liquid in the lubricating film.

The bulk viscosity of a liquid can be accurately measured by various methods. For aqueous solutions we recommend glass capillary viscometers and falling ball viscometers. The falling ball viscometers measure the dynamic viscosity of liquids, and the glass capillary viscometers measure the kinematic viscosity (dynamic viscosity / density). Those viscometers are very inexpensive, cover a wide range of viscosities, use relatively small amount of liquid and are easy to use. Those viscometers are widely available, say, from Cole-Parmer (tel: 1-800-323-4340).

The best way to get a quantitative measure of sensation in thin films is to measure the coefficient of friction on the skin or skin substitute. The measurement of static friction on flat surfaces is not hard, but this measurement may not be possible on living skin. For a skin substitute, any leather-like substance which adsorbs skin-like oils would work. There is no commercially available equipment that measures the coefficient of friction between sliding surfaces.

Any method which will give a measure of the normal load between the surfaces and of the tangential force necessary to cause sliding can be used to determine the friction coefficient. The methods include the use of a simple weight hanging on a pulley, the tilting of an inclined plane, the deflexion of a pendulum or of a spring, the measurement of the rate of deceleration of the moving solid, and the use of piezo-electric crystals or resistance strain gauges or electrical capacity methods to measure the normal and tangential forces between the moving surfaces.



**Figure 12.** Apparatus to measure the friction between surfaces at very small load, adapted from Whitehead, 1950.

The apparatus to accurately measure the friction between sliding fingers is depicted in figure 12. The lower surface is in the form of a small flat piece of metal A with the top surface covered by a skin or skin substitute. This piece is mounted at the edge of a turntable B. The turntable is driven by an electric motor and the sliding speed of the surface B can be adjusted. The upper surface or slider C, is in the form of an artificial finger possibly made of rubber and covered by a skin or skin substitute. It is mounted at one end of a steel wire D. The other end of the wire is suitably clamped at the end E of a lever arm F. The load is applied to the slider by raising the remote end G of the lever arm and so flexing the wire in a vertical plane. By using wires of various thicknesses a practicable range of loads may be obtained. When the lower surface is set in motion it drags the slider with it and flexes the wire D in a horizontal direction until the restoring force is equal to the friction. The deflection of D in the horizontal direction is thus a measure of the frictional force. This force can be recorded electrically in the following way. The movement of D deflects the needle H which rotates a moving coil supported between a pair of soft iron pole-pieces (K). The magnetic coils around the pole pieces are energized by an alternating current. Deflection of the needle alters the induced voltage in the moving coil and this is connected via an amplifier to a suitable recorder.

## Summary, Conclusion and Opinion

We considered the factors controlling tactual sensations when aqueous solutions are placed between fingers, between fingers and the palm of the hand or when these contacts are made through another media, say, paper or contact lens.

### Summary

We noted that touch sensation arises from the neural signals of the nerve ending receptors beneath the surface of the skin. Only two of the six components of stress are relevant in stimulating those nerve receptors: the normal stress (pressure) and shear stress. The normal stress is experienced as pressure when the fingers are pressed together or as tacky or sticky when the fingers are pulled apart. The shear stress gives rise to the sensation of slipperiness or friction when the fingers are rubbed against each other.

Static pressure between the fingers and palms, separated by an aqueous solution, does not give rise to sensations different than when there is no solution. However, a tension in the solution can make the fingers feel sticky when they are pulled apart. Lateral rubbing gives rise to special sensations of slipperiness or friction. Basically, we sense the resistance to sliding.

The experiences of stickiness and slipperiness depend strongly on the thickness of the lubricating film. Thin molecular films give rise to special sensations because they are adsorbed on the skin and form composite surfaces and are effected by both the skin and fluid. The exact chemistry and mechanics of these ultra thin lubricating films is not perfectly understood. However, the theory of boundary lubrication which was developed for lubrication of metals by adsorbed films apparently applies directly to skin because the adsorbed layers on metals and skin are similar and assume that the resistance to motion is due to intermolecular forces at points. The most systematic formulation of this theory is due to the work of Hardy, who showed that the friction was not only influenced by the chemical nature of the lubricant but also by the nature of the underlying surface. Working with homologous series of paraffins, alcohols, and fatty acids on various surfaces, Hardy found that the static friction was a function of separate contributions by the solid surfaces, the chemical series to which the lubricant belonged and the number of carbon atoms in its chain. To interpret these data, Hardy assumed that the friction between unlubricated surfaces is due to surface fields of force. When the lubricant is added, the lubricant molecules are physically adsorbed and orient themselves at each of the solid surfaces to form a unimolecular film. Since the polar groups adhere to the metal (skin) surface, contact takes place, not between the metal (skin) surfaces themselves, but between the non-polar groups at the other

end of the lubricant molecules. Slip, then, takes place between these non-polar sheets, and the efficiency of the boundary lubricant is measured by the extent to which these films can mask the field of force of the underlying surface. It is apparent that this effect will depend on the polarity of the lubricant molecule and on its chain length.

### Conclusion

The following results were obtained in our study:

1. The well-developed theory of lubrication applies to lubrication of the fingers with aqueous solutions. There are two extreme regimes of lubrication: the hydrodynamic regime and boundary lubrication regime. First, in the hydrodynamic regime, the pressures that carry load are in fluid film alone. These pressure can develop only when there is a relative sliding motion between the sliding boundaries (fingers) and the viscosity of the lubrication fluid is large enough to open the gap by hydrodynamic pressures. In boundary lubrication, the loading is supported by direct contact. In this state, the thickness of the lubricating film can be insensible, one micron or even molecular dimension. The lubricating film in this state is subject to short range forces like Van der Waals forces which endow the film with properties which depend on the boundary surfaces as well as the chemical composition of the liquid in the layer. A mixed state of hydrodynamic-boundary lubrication occurs from thin films in which part of the load is carried by hydrodynamic forces and a part by direct contact.
2. Adsorption of surface active agents onto metal surfaces is a key concept in the lubrication of metals. Surprisingly, this concept works well for aqueous films controlling touch sensation. Surface active agents adsorb at solid-liquid surfaces as they do at liquid-liquid surfaces. In the liquid-liquid case, the heads of a surfactant molecule like water and the tails like oil (see figure 5). They orient themselves and are attracted to the liquid-liquid interface forming an adsorption layer at the interface. In the solid-metal case, the active agents are salts, fatty acids and oils. They line up with active heads adhering to solid surfaces forming adsorption layers. Anionic surfactants (active) make the skin very slippery. Non-ionic surfactants are inactive. Soaps act as anionic surfactants on the skin.



### Opinion

It is our opinion that the most important factors in touch sensation are the adsorbed surface active agents in the aqueous solution. We further believe that a classification of surfactants as rich as the ones known for metals can be achieved.

The best way to get a quantitative measure of sensation is to measure the coefficient of static friction on the skin or skin substitute. The measurement of static friction on flat surfaces are not hard, but this measurement may not be possible on living skin. For a skin substitute, any leather-like substance which adsorbs skin-like oils would work.

The problem of touch sensation in thick films of high viscosity is not difficult. When the viscosity and thickness are the same, the film gives rise to similar rubbing sensations, which are the same in all Newtonian fluids.

Qualitatively, we can progress in classifying surface active substances for aqueous solutions from touch sensations, as in our Table 1. It is probable that considerable information about skin active surfactants can be found in industries manufacturing soaps, detergents, shaving creams and shampoos.