Chapter 1
Introduction

Skin is the outer layer covering a human or animal body. It is the largest organ and for humans covers an average surface area of 1.5–2 m^2. Its function is to protect the body from physical and environmental assaults, and to provide sensation, heat regulation, water resistance, and other such functions. Skin ages over time, resulting in changes in skin properties. The skin aging process is the result of two biological processes called intrinsic aging, where changes accumulate over a lifetime, and extrinsic aging, attributed to environmental influences. Aging is a degeneration of tissue (such as degradation of mechanical properties as a result of decreases in collagen) and loss of lipids (responsible for creating a water barrier), and leads to various issues such as sagging skin and wrinkles. In addition to aging, skin also is damaged as it goes through various daily activities. Environmental conditions, such as dry and cold weather, can reduce the moisture content of skin temporarily, and can induce epidermal hyperplasia, mast cell degranulation, cytokine secretion, increased skin roughness, and physical discomfort (Harding et al. 2000; Leyden and Rawlings 2002; Tang and Bhushan 2010; Bhushan 2012; Bhushan et al. 2012).

For healthy and beautiful human skin, cleaning and maintenance of skin is a daily process. The demand for skin care products that prevent or relieve skin damage has created a $2 billion dollar industry in the U.S. alone, as of 2015. As commonly-used skin care products, skin cream and moisturizer increase the moisture content in the outer layer of skin. This hydration creates a smooth, soft, moist, and flexible surface, and alters the tribological properties (surface roughness, adhesion, friction, and wear) and mechanical properties (elastic modulus, hardness, and viscous damping) of the skin surface. Hydration changes the surface feel or tactile perception of cream treated skin when it touches a surface. Beauty care science is interested in the way in which skin cream changes the tribological and mechanical properties, tactile perception, and the effect of the operating environment of skin, as these properties are closely tied to product performance and, ultimately, guide consumers' likes or dislikes of the product (Bhushan et al. 2010,

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2012; Tang and Bhushan 2010; Tang et al. 2010a, b; Bhushan and Tang 2011; Bhushan 2012; Chen and Bhushan 2013).

For a primer to tribology, see Appendix A.

1.1 Tribological and Mechanical Properties and Triboelectric Effects

The tribological and mechanical properties of human skin were reported as early as the 1950s (Naylor 1955). Since then, many studies have focused on evaluating the frictional properties of skin and the factors affecting friction. Friction is resistance to sliding in a contact, and is a measure of tactile perception (Bhushan 2001, 2013a, b). There are various factors that affect friction between skin and an object that comes into contact with it. For example, friction between skin and wet fabric is reported to be higher than that with dry fabric. To study the effects of age, sex, and anatomical region on frictional properties, various studies on human skin have been carried out (Cua et al. 1990; Sivamani et al. 2003b; Kwiatkowka et al. 2009). Cua et al. (1990) reported significant differences in friction within various anatomical regions—forehead, arm, palm, abdomen, back, thigh, and ankle.

Skin is affected easily by the environment. A high temperature and low humidity environment will increase the rate of transepidermal water loss, cause dehydration of the stratum corneum, and cause scaling, cracking, and electrostatic charging of skin surface. On the other hand, a high humidity environment hydrates the skin surface and creates soft, smooth, flexible, and healthy-looking skin with lower electrostatic charge build up. It is established that the state of skin hydration affects friction (Highley et al. 1977; Nacht et al. 1981; Cua et al. 1990; Gerhardt et al. 2008; Kwiatkowska et al. 2009). Dry skin exhibits lower friction than moist skin. With the application of water or moisturizer on a skin surface or in a humid environment, a positive linear correlation exists between skin moisture and the coefficient of friction. As compared to male skin, female skin shows higher moisture sensitivity and a higher coefficient of friction.

Studies have been carried out in order to quantify the efficiency of skin care products to study their effect on friction (EI-Shimi 1977; Cua et al. 1990; Zhang and Mak 1999; Koudine et al. 2000; Sivamani et al. 2003a, b; Tang et al. 2008, 2015; Bhushan 2012; Bhushan et al. 2012). Skin treatment increases the moisture content in the outer skin layer. The hydration creates a smooth, soft, and elastic surface leading to higher real area of contact, adhesion, and friction, which results in a change in tactile perception. Thus, after treatment, the skin surface is perceived as sticky or greasy, but because this change improves moistness, softness, and elasticity, the treated skin is perceived as more comfortable than virgin skin.

Since solid surfaces are not microscopically smooth, many interactions between skin-skin and other surfaces in contact take place at micro/nanoasperities with linear dimension ranging from a few hundred nm to hundreds of μm (Bhushan 2001, 2013a, b). Therefore, the study of the coefficient of friction and adhesive force on the nanoscale is useful because it allows for a better understanding of the mechanisms behind how the skin cream interacts with skin. Atomic force microscopes (AFM) and nanoindenters have made it possible to study the tribological and mechanical properties of skin and evaluate the effect of cream on the nanoscale (Bhushan and Li 2003; Bhushan 2008, 2010a, b, 2011, 2012, 2013a, b). The AFM uses a sharp tip with a radius typically less than 10 nm, which allows the simulation of single asperity contact for measurement of the film thickness, friction, adhesion, and wear. A nanoindenter uses a sharp tip with a radius typically on the order of 50–100 nm, which allows measurement of mechanical properties on the nanoscale, relevant for individual asperity contacts.

Rat skin and pig skin are commonly used as substitutes for human skin for cosmetic research (Bhushan et al. 2010, 2012; Tang and Bhushan 2010; Tang et al. 2010a, b). In cosmetic science, synthetic skins are also used in place of human tissue. Various synthetic skins have been used for cosmetic research (Bhushan and Tang 2011; Chen and Bhushan 2013). Nanotribological and macrotribological data for skins with and without cream treatment as well as at various temperatures and humidities has been reported by Tang and Bhushan (2010), Tang et al. (2010a, b), and Bhushan et al. (2012). Nanomechanical data of various skins with and without cream treatments have been reported by Bhushan et al. (2010, 2012). These data are useful in bridging the gap between the nano- and macroscale data, as well as to gain an understanding of the mechanisms behind how skin cream interacts with skin.

It is well known that friction force is quantized with the number of molecular layers in very thin liquid films (Israelachvili et al. 1988). Cream rheology is expected to be a function of its thickness as well as the sliding velocity (shear thinning) and normal load during its application (Liu and Bhushan 2003; Tambe and Bhushan 2005; Tao and Bhushan 2007). Tang and Bhushan (2010), Tang et al. (2010a), and Bhushan et al. (2012) studied the effect of the effect of cream thickness, normal load, and velocity on the nanotribological properties of skin with and without cream treatment.

The mechanical properties of skin are of importance to prevent damage and maintain good feel. For example, mechanical properties influence skin's resistance to laceration during impact injury (Karlson 1982). They are important indicators of pathological situations. Precise knowledge of the mechanical properties of skin is also of interest to plastic surgeons in designing the size, shape, and orientation of skin grafts (Lanir and Fung 1974b). The mechanical properties of skin are affected by the level of hydration (Aubert et al. 1985; Murray et al. 1996; Dobrev 2000). Extensibility and viscoelasticity are markedly influenced by the water content of the stratum corneum, which is the top layer of skin. The main objective of the application of skin cream is to assist the stratum corneum in restoring lost moisture. Many macroscale studies have focused on the mechanical properties of skin with and without skin treatment such as elastic-plastic deformation behavior, hardness, Young's modulus of elasticity, time dependent creep, and relaxation properties (Lanir and Fung, 1974a, b; Dombi et al. 1993; Piérard et al. 1999; Őzyazgan et al. 2002, Del Prete et al. 2004; Sanders 1973; Diridollou et al. 1998; Pan et al. 1998; Falanga and Bucalo 1993). Nanoscale studies using an AFM and nanoindenter have focused on the mechanical properties of skin with and without cream treatments (Yuan and Verma 2006; Kendall et al. 2007; Bhushan et al. 2010, 2012).

As skin is the outer layer of our body, it is the first line of defense against external objects. However, it often fails in contact with sharp objects (scratch action). AFM has been used to perform scratch tests on skin by Bhushan et al. (2010). The experiments have been performed to understand how skin with a cream film fails at light loads, and how the skin cream acts as a protective coating. In addition, in situ deformation experiments with an AFM to follow the progress on morphological changes and deformation in skin subjected to tensile loading have been carried out by Tang et al. (2010b).

In addition to change in the mechanical and tribological properties of skin by moistening and softening skin surface, skin cream also can reduce the electrostatic charges on skin surface. The stratum corneum of skin is a good insulator with high electrical resistance, around hundreds of kilo-ohms (Johnson and Corah 1963). Due to the high electrical resistance, charges on the skin surface are difficult to dissipate, especially in a low humidity environment. These electrostatic charges usually cause unpleasant and unhealthy effects, such as electric shocks, dry skin, headaches, and tiredness (Jonassen 1998). Skin cream is known to affect the electrical properties of skin. Understanding the mechanisms behind charge buildup and how to control it is a focal point in designing effective skin cream products.

The effect of skin cream on the electrical properties of skin surface on the macroscale has been studied (Blichmann et al. 1989; Lodén and Lindberg 1991; Sivamani et al. 2003a). Surface potential studies on the skin surface with and without skin cream and different humidity levels on the nanoscale have been carried out using AFM-based Kelvin probe method by Tang et al. (2010a, b). Nanoscale data allows for a better understanding of the mechanisms behind how skin cream interacts with skin and affects the electrical properties of skin. Since the charge is proportional to the contact surface potential (Son and Lee 2008), the change of surface potential can reflect the change of surface charge.

Macroscale rubbing is a general method to charge a sample surface and quantitatively evaluate the static charge during rubbing. Since there are also many microspherical particles in the environment interacting with skin surface and inducing static charge on the microscale, the triboelectrification of skin using microscale rubbing have also been used. Many investigations have reported the dependence of the charging behavior on friction, velocity, normal load, and rubbing time for insulator material, such as polymer, human hair, and animal skin (Wåhlin and Bäckström 1974; Ohara 1978; Ohara et al. 1990; Greason et al. 2004; Seshadri and Bhushan 2008b; Tang et al. 2010a, b).

1.2 Tactile Perception

Humans traditionally are described as possessing five senses (sight, smell, taste, hearing, and touch), each of which has a corresponding receptor organ (eyes, nose, tongue, ears, and skin, respectively). Tactile perception (also known as "somatic sense" or "touch") is accomplished by the skin. Tactile perception of the surface as being soft and smooth is important in many applications, such as touch with skin or fabrics (Katz 1989; Hollins et al. 1998; Scheibert et al. 2009). Smooth skin is perceived as young skin. Therefore, most humans want smooth skin because it makes them look and feel younger. Though we describe tactile perception as a single sensation, it is the result of nervous response to the external stimuli causing stretch of the skin, pressure on the skin, temperature, and vibrations. To arrive at the perception that skin is smooth, our brains integrate data on skin's stretch, pressure, temperature, and vibrations.

When human skin touches human skin (whether between two people or when one person touches their own skin), the condition of the skin of both sides of the touch is of importance to the perception of that touch. Skin that is perceived as smooth is more pleasing to touch, and is more pleasing to have touch. As an example, if fingers touch a face, it is more pleasing to the owner of the face if the fingers are not rough, and it is more pleasing to the owner of the fingers if the face is smooth.

The perception and integration of the four sub-sensations of stretch, pressure, temperature, and vibration into a single sense of touch is affected by the interfacial condition between the skin receiving the stimulus and the object causing the stimulus. When skin is hydrated and an external stimulus is applied, those four sub-sensations can be perceived more acutely. When skin is dry, they may be perceived less acutely. This is important to the skin's functions of thermoregulation, injury prevention, general comfort, and other functions. Skin creams can increase the skin's hydration, and therefore its perception of external stimuli, providing faster and more critical responses.

When one applies skin cream to the body, interfacial friction results in vibrations carried by nerves to the brain. The brain perceives skin smoothness during the application of skin cream by sensing, among other things, skin vibrations. Therefore, a more direct measure of the degree of skin smoothness is to measure interface vibrations created during application and touch. Vibration data, which correlate to friction data, are presented.

1.3 Application of Skin Cream, Tactile Perception, and Role of Tribology

When skin cream is applied to the skin surface, the primary penetration pathway of cream compounds is through the intercellular lipids of the stratum corneum, though it does not exclude the possibility that the compounds can pass into the corneocytes (Bronaugh and Maibach 1999; Morganti et al. 2001); see Fig. 1.1. In terms of percutaneous absorption, the compounds of skin cream dissolve/partition into the surface lipids of the stratum corneum, diffuse through the lamellar domains of the stratum corneum, partition from the stratum corneum into the more hydrophilic

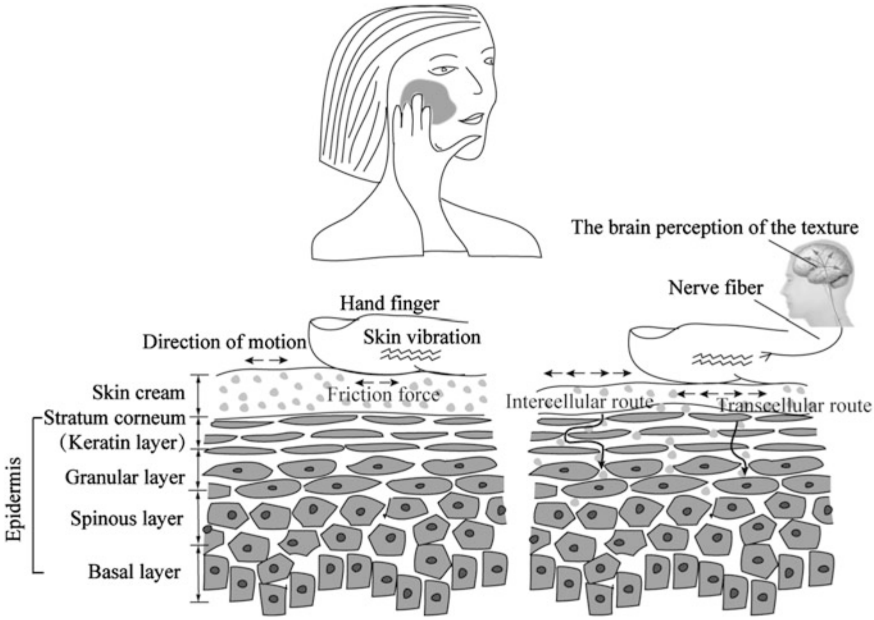

Fig. 1.1 Schematics illustrating the application process of skin cream, as well as the route of penetration of skin cream, and the relationship between skin vibration and brain perception of the skin texture (adapted from Tang and Bhushan 2010)

viable epidermis, and diffuse through the epidermis and dermis (Morganti et al. 2001). Through these interactions with skin, an efficient skin cream can cause a drastic change in tactile perception.

Figure 1.1 also schematically illustrates the application process of skin cream, along with the mechanisms behind the interaction that make friction important to the tactile perception of skin cream (Tang and Bhushan 2010). Skin cream is usually applied at a frequency of 1–10 Hz. Adhesion and friction properties are governed by the physical and chemical properties of both the skin and the rubbing surface. The vibrations in the process of rubbing are highly dependent on the friction and adhesion properties, as well as the dynamic viscosity of skin cream at the relevant film thickness and shear rate (Giasson et al. 1997; Luengo et al. 1997; Vicente et al. 2006). For moist, soft, and smooth skin after cream treatment, the friction and adhesion of skin would be higher than that for a dry, hard, and rough skin (EI-Shimi 1977; Nacht et al. 1981; Egawa et al. 2002; Bhushan 2012; Bhushan et al. 2012).

Usually there are three phases of tactile perception in the application process of skin cream: "slippery," "sticky," and "smooth or moist," corresponding to the three phases of friction. In the initial phase, when skin cream is first applied, the cream film is relatively thick, and there is less asperity contact. The contact with the skin surface operates essentially in the hydrodynamic or mixed lubrication regime, so the coefficient of friction is low, and the skin feels slippery. In the second phase, as the cream film becomes thinner and is absorbed, the contact with the skin transitions into the boundary lubrication regime. Meanwhile, the skin is moistened and softened by the cream, which results in high adhesive force and friction force, so the skin feels sticky prior to complete absorption. In the third phase, water evaporates from the skin, along with other physical and chemical changes resulting from the absorption of skin cream. In this phase, the coefficient of friction and adhesive force reduce such that skin no longer feels sticky, but not to pre-application levels, so skin instead feels smooth. The duration of the third phase is highly related to the quality of cream and the operating environment. For a high-performance cream, high friction may last for over a day, while for a low-performance cream, it may last for less than an hour. Tribological and mechanical studies provide a straightforward and valuable way to investigate how the properties of skin are altered with various skin care products.

The vibrations generated during the rubbing affect the tactile perception of the skin by the brain (Katz 1989; Hollins et al. 1998; Scheibert et al. 2009). Many studies show that there is a correlation between changes in the sensory perception and friction of skin (Tang et al. 2015; Ding and Bhushan 2016).

1.4 Organization of the Book

In this book, we present an overview of surface roughness, friction, adhesion, dynamic viscosity, and wear resistance (durability) of skin with and without cream treatment. The effect of cream thickness, velocity, normal load, temperature, and humidity on the adhesion, friction, nanomechanical properties, and surface charging of skin with and without cream treatment using an AFM and nanoindenter are summarized. Next, nanotribological and nanomechanical data on two relatively inexpensive synthetic skins with and without cream treatment is presented. Finally, data on tactile perception of skin with and without cream treatment is presented.

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