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The Appearance of Human Skin: A Survey

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The Appearance of Human Skin: A Survey

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Abstract

Skin is the outer-most tissue of the human body. As a result, people are very aware of, and very sensitive to, the appearance of their skin. Consequently, skin appearance has been a subject of great interest in various fields of science and technology. In particular, research on skin appearance has been intensely pursued in the fields of computer graphics, computer vision, cosmetology, and medicine. In this survey, we review the most prominent results related to skin in these fields and show how these seemingly disconnected studies are related to one another. In each of the fields, the optical behaviors of specific skin components have been studied from the viewpoint of the specific objectives of the field. However, the different components of skin produce different types of optical phenomena that are determined by their physio-anatomical characteristics (sizes, shapes, and functions of the

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components). The final appearance of skin has contributions from complex optical interactions of many different skin components with light. In order to view these interactions in a unified manner, we describe and categorize past works based on the physiological and anatomical characteristics of the various skin components.

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1

Why is Skin Appearance Important?

Skin is the outermost tissue of the human body. As a result, people are very aware of, and very sensitive to, the appearance of their skin. Consequently, skin appearance has been a subject of great interest in several fields of science and technology. As shown in Figure 1.1, research on skin appearance has been intensely pursued in the fields of medicine, cosmetology, computer graphics, and computer vision. Since the goals of these fields are very different, each field has tended to focus on specific aspects of the appearance of skin. The goal of this study is to present a comprehensive survey that includes the most prominent results related to skin in these different fields and show how these seemingly disconnected studies are closely related.

In the field of computer graphics, computational modeling of the appearance of skin is today considered to be a very important topic. Such skin appearance models are widely used to render fictional human characters in movies, commercials, and video games. For these "virtual actors" to appear realistic and be seamlessly integrated into a scene, it is crucial that their skin appearance accurately captures all the subtleties of actual human skin under various viewing and lighting conditions. Although great progress has been made in making rendered skin

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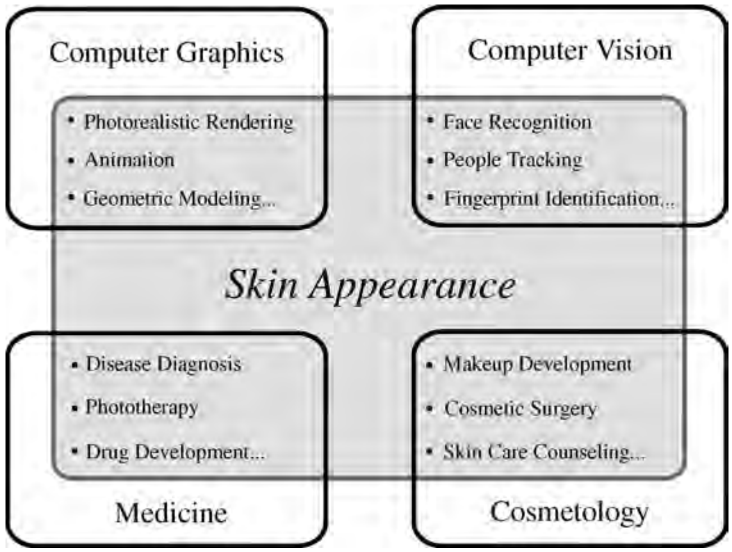

Fig. 1.1 Many different research fields have conducted extensive research on the appearance of skin. The fields of medicine, cosmetology, computer graphics, and computer vision have been most active in the study of skin appearance. Studies in each of these fields provide us knowledge and insights regarding different aspects of skin appearance.

appear realistic, it is still far from perfect and is easily recognized as being rendered rather than real. In short, a computationally efficient and yet realistic skin model remains an open problem in computer graphics.

In computer vision, a detailed and accurate model of skin appearance is of great value in identifying individuals. For instance, human identification based on fingerprints has made substantial progress and is now a widely used biometric technology. It is now widely acknowledged that accurate models of the appearance of skin in other parts of the body could be useful for human identification as well. For instance, technologies that recognize the pattern of blood vessels in the palm and the finger have been recently developed and have shown good performance in identification. In order to reliably exploit similar signatures of skin appearance from other body regions, we need a more comprehensive understanding of the optical characteristics of skin.

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Skin also has aesthetic relevance. The desire to have beautiful and healthy looking skin has been a centuries-old quest for humans. Skin with brighter complexion and smoother surface tends to be perceived as being healthier and more attractive. Making skin appear beautiful is the primary goal of cosmetology. For instance, foundations are widely used to hide skin imperfections and make skin look younger. Despite the enormous investments made in skin research, today's foundations are far from perfect. While they may hide imperfections and make skin appear more uniform, the final appearance of skin coated with a foundation always has an artificial look to it. Recently, skin counseling systems have been developed to help a person identify cosmetic products that would be most suited to them. Such systems can also benefit from more accurate and detailed models of skin appearance.

Needless to say, the appearance of skin is of vital importance to the field of medicine. During the diagnosis of skin diseases, careful observation and assessment of the appearance of the diseased area is always the first and most important step. Recently, photo-diagnosis and photo-therapy have become popular methods for treating skin diseases. In these techniques, light is used to detect and treat lesions in the skin. Such techniques are non-invasive and hence patients are not subjected to pain and scars during the treatment. In order to increase the precision of such systems, we need more precise models of the interaction of light with dermal tissues.

In this survey, we will summarize and relate studies on skin appearance conducted in the above fields. Our goal is to present the disconnected works in these different areas within a single unified framework. In each of the above fields, the optical behaviors of specific skin components have been studied from the viewpoint of the specific objectives of the field. However, the different components of skin produce different types of optical phenomena that are determined by their physio-anatomical characteristics (sizes, shapes, and functions of the components). The final appearance of skin has contributions from complex optical interactions of many different skin components with light. In order to view these interactions in a unified manner, it is meaningful to describe and categorize past works based on the physiological and anatomical characteristics of the various skin components. To this end,

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we will first outline the physio-anatomical characteristics of skin that are important to its appearance. Then, we will review previous studies that have been conducted on each of the structural components of skin.

We will start our survey by describing the basic functions of human skin in Section 1.1. This knowledge is necessary to understand the physio-anatomical properties of the components of skin. In Section 1.2, we will propose a taxonomy of skin appearance that serves as the basic structure of our survey. In this taxonomy, we summarize the important physio-anatomical components of skin and the optical phenomena they produce. In Chapter 2, we will describe in detail the physio-anatomical structure and character of each skin component. In Chapter 3, we will review studies on skin appearance that have been conducted in the four fields shown in Figure 1.1. We hope our survey will have two effects. The first is to broaden and deepen the reader's understanding of skin appearance. The second is to spur new interdisciplinary research on skin appearance.

1.1 What is Skin?

Skin is the outermost tissue of the body and the largest organ in terms of both weight and surface area. It has an area of approximately $16,000\,\mathrm{cm}^2$ for an adult and represents about 8% of the body weight. As seen in Figure 1.2, skin has a very complex structure that consists of many components. Cells, fibers and other components make up several different layers that give skin a multi-layered structure. Veins, capillaries and nerves form vast networks inside this structure. In addition, hairs stick out from the inside of skin. Numerous fine hair furrows are scattered over the surface of skin.

Skin performs a wide variety of functions resulting from chemical and physical reactions inside these components. The major function of skin is to act as a barrier to the exterior environment. It protects the body from friction and impact wounds with its flexibility and toughness. Harmful chemicals, bacteria, viruses, and ultraviolet light are also prevented from entering the body by the skin. It also prevents water loss and regulates body temperature by blood flow and evaporation of sweat. These functionalities are critical to our well-being. The secretion

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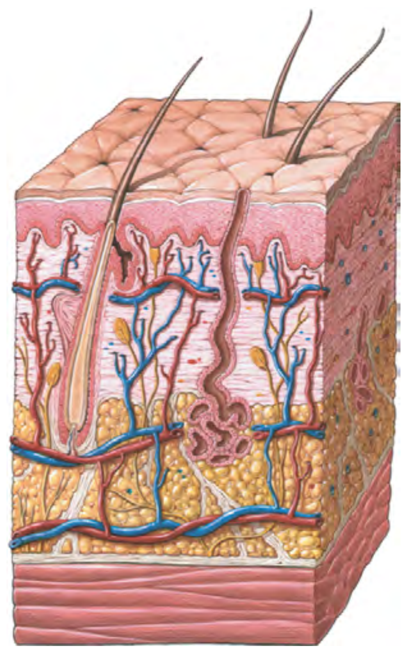

Fig. 1.2 A cross-sectional schematic diagram of skin. Skin is a complex multi-layered tissue consisting of various types of components, including veins, capillaries, hairs, cells, fibers, etc. (Image courtesy of A.D.A.M.)

of sweat and skin lipid cause the elimination of a number of harmful substances resulting from metabolic activities in the intestines and the liver. Furthermore, skin has a large number of nerve fibers and nerve endings that enable it to act as a sensory organ. When skin is exposed to sunlight, it can produce vitamin D, a vital chemical substance for the body [144].

These functions of skin tend to vary in degrees according to age, race, gender, and individual. For instance, older skin tends to lose its flexibility and toughness because the structure of skin slowly denatures with age. The light-protection ability of skin among different races varies due to the differences in the volume of melanin which absorbs ultraviolet light. These functional differences are in most cases a result of physio-anatomical variations within the structure of skin. It is these physio-anatomical variations that lead to the diverse appearances of skin. Hence, in order to understand the appearance of skin, it is crucial

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to understand the physiology and anatomy of skin. In the next section, we will present a taxonomy of skin appearance that is based on physiology and anatomy. Then, in Chapter 2, we will use this taxonomy to describe the physio-anatomical properties of the various skin components.

1.2 Taxonomy of Human Skin Appearance

In order to understand the appearance of skin, it is important to understand the optical/visual properties of the constituent components of skin. In this section, we present a hierarchical representation of skin components that is based on the scale of the optical processes induced by the components.

As shown in Figure 1.3, the components of skin appearance can be categorized along an axis that represents spatial scale. Here, we only focus on skin components that have a measurable contribution to its appearance. We refer to the smallest components as *microscale*, larger components as *mesoscale*, and the largest components as *macroscale*. Each scale is subdivided into finer levels based on physiology and anatomy. As a result, skin can be viewed as a hierarchical organ in which components at one level serve as building blocks to constitute higher-level components. The components in each level have their own visual properties. Each of these visual properties is studied based on its underlying physical phenomena. The scattering or appearance model that describes these phenomena are listed in the rightmost column in Figure 1.3.

1.2.1 Microscale

Cellular-level elements and *skin layers* constitute the finest scale of the physio-anatomical structure of skin. The sizes of these components are very small and they are barely visible to the naked eye. The visual properties of these elements are the result of their optical interactions with incident light. From an optical viewpoint, the dominant effects produced at this scale are scattering and absorption. These effects vary depending on the sizes, shapes, and optical parameters such as the refractive indices of the elements. For example, fibers and organelles

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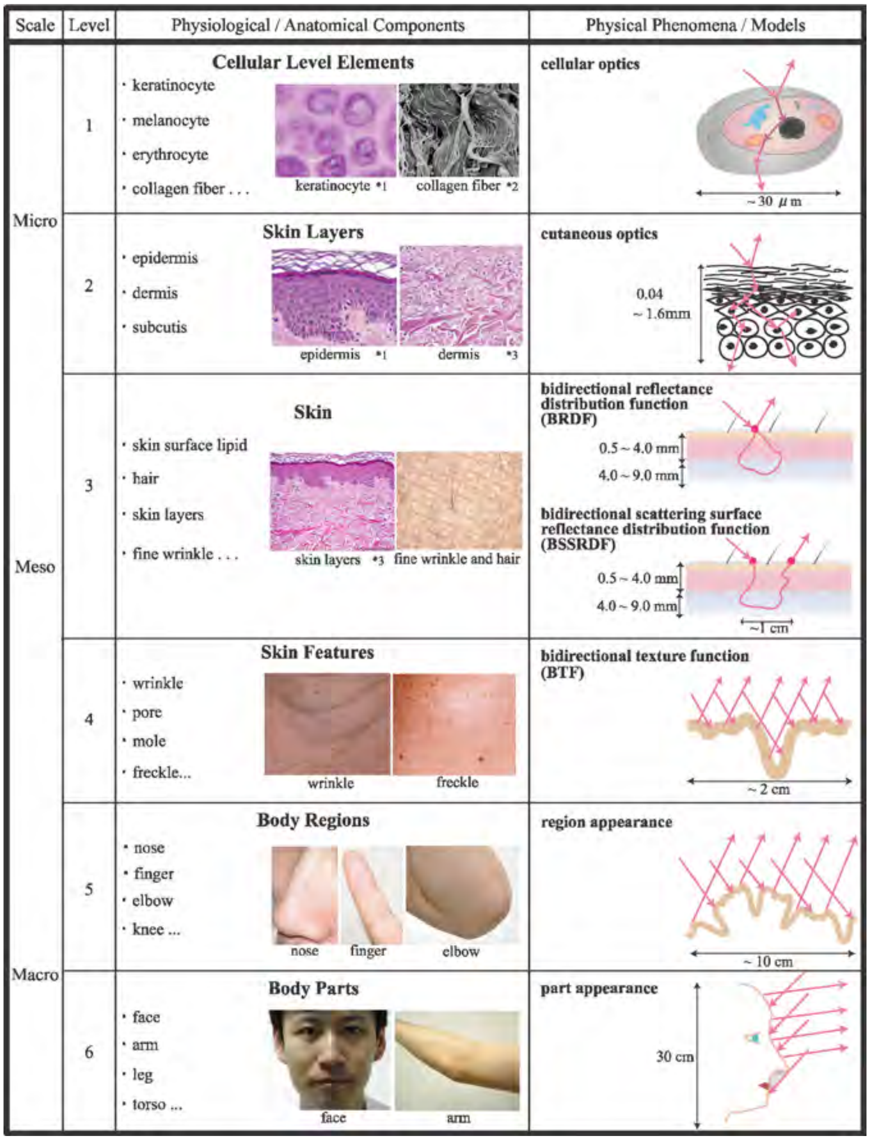

Fig. 1.3 Taxonomy of the appearance of skin. The components of skin appearance can be hierarchically categorized along an axis that represents physical scale. We review the studies on skin appearance done in different fields based on this taxonomy. *1 Photo courtesy of Chrustopher Shea, MD, Duke University Medical Center; *2 Photo from Nanoworld Image Gallery, Centre for Microscopy and Micronanoanalysis, The University of Queensland; *3 Photo courtesy of T. L. Ray, MD, University of Iowa College of Medicine.

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that are found in cells behave as strong scatterers. The cell membranes and the blood vessel walls behave like reflectors and refractors. The aggregation of these optical phenomena determine the visual properties of the components at higher levels. Some of these elements, such as organelles, have sizes close to the wavelength of visible light. Hence, the optical properties at this level must be studied using wave optics.

The cellular-level elements constitute several primary layers of skin: epidermis, dermis, and subcutis, which are classified in Level 2 in Figure 1.3. These layers have very different structures and constituents and hence their physiological characteristics are different from each other. For example, the epidermis is a very thin layer (0.2 mm on average) which mainly consists of cells. On the other hand, the dermis is a thick layer (2 mm on average) composed of more fibers compared to the epidermis. These physio-anatomical differences have large influences on the light propagation in these layers and lead to very different optical effects. For example, the epidermis is a transparent optical medium and the dermis is a turbid medium. These optical differences enable us to view these layers as the primary optical media for describing the optical properties of higher-level components.

1.2.2 Mesoscale

Skin and *skin features* constitute the mesoscale. At this scale, the components become visible to the naked eye. The visual properties of these components are mainly determined by the optical phenomena that are induced by finer-scale components — components in the microscale.

Skin, as categorized in Level 3 in Figure 1.3, is composed of *skin layers*, *skin surface lipid*, *hairs*, *fine wrinkles*, etc. The appearance of skin can be viewed as the combined effect of the optical phenomena induced by these substructures. Skin layers include the lower-level components in Level 2 — epidermis, dermis, and subcutis. Visual property of skin layers can also be considered as the combined effect of the optical events that take place in each of these layers. Hence, understanding the optical properties in the microscale is crucial to understand the visual properties of the components in the mesoscale.

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Skin surface lipids, hairs, and fine wrinkles are found on the surface of skin. They contribute interesting optical effects. For example, the appearance of skin after sweating usually becomes more glossy. This change of appearance is mainly due to the reflection of incident light by the film of skin surface lipids. The appearance of skin with dense hair and fine wrinkles tends to be more matte. This is because of the additional scattering of incident light by the hairs and fine wrinkles.

Skin constitutes higher level components – skin features such as freckles, moles, wrinkles, and pores (see Level 4 in Figure 1.3). These features can be viewed as morphological variations of skin. For example, freckles and moles tend to produce two-dimensional variation in skin color. In contrast, wrinkles cause deep furrows and flat planes and are inherently three-dimensional textures. Hence, the visual properties of skin features are influenced by not only the optical properties of the skin layers but also the morphology of skin.

1.2.3 Macroscale

Body regions and *body parts* are classified as macroscale and physiologically assigned to Level 5 and Level 6, respectively (see Figure 1.3). The appearance of skin varies across different regions of the body. This is because the physio-anatomical characteristics of the lower-level components can differ significantly from one region of the body to another. For example, the nose and the forehead have greater amounts of skin surface lipid compared to the cheek. As a result, the nose and the forehead tend to appear more glossy than the cheek. To our knowledge, there are no physical models that describe these appearance variations over the body in a unified framework. Body parts such as the face, arm, leg, and torso are clusters of body regions. The appearance of each body part includes the appearances of the body regions that constitute it. Again, we are not aware of any physical or empirical model for describing part appearances in a unified manner.

It is interesting to note that the four fields that have been involved in skin research have tended to focus on different scales or levels of skin appearance. In computer graphics and computer vision, components in the visible scale have been studied. This is because the main

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objectives in these fields are to render and recognize skin appearance. Thus, previous work in graphics and vision provide us with knowledge about the visual properties of skin mainly at the meso and macroscales. On the other hand, research in medicine has focused on lower-level elements. This is because skin diseases are usually caused by disorders in the microscale components. Thus, past work in medicine provides us with knowledge about the optical properties of skin at the microscale. By reviewing work in these different fields, we can span all the scales of skin appearance and, at the same time, describe all of the previous works in a consistent manner.

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