



Review

Models for fingerprint pattern formation

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Abstract

There is currently no general agreement on the process by which fingerprint (epidermal ridge) patterns form. Nevertheless, many possible mechanisms have been proposed. Based on an extensive literature review and mathematical modeling we argue that the pattern arises as the result of a buckling (folding) process in a cell layer of the epidermis. Using this model we were able to explain the long-known observation that the pattern type is related to the geometry of the embryonal fingertip.

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1. Introduction

The growing importance of fingerprints (epidermal ridges) for our every-day life can hardly be overemphasized, especially in a time when biometric recognition techniques augment the

more traditional forensic applications. It is therefore not surprising that fingerprints have been an object of scientific curiosity for a long time. The focus of research included diverse fields such as anthropology, embryology, genetics, statistics of fingerprint patterns, biometric and forensic applications [1]. But despite the importance of fingerprint patterns and the significant empirical research a commonly accepted mechanism by which fingerprint patterns form has not yet emerged.

This lack of an agreement on the origin of fingerprints has clear implications for forensic science. Models for the distribution of minutiae and other important features for

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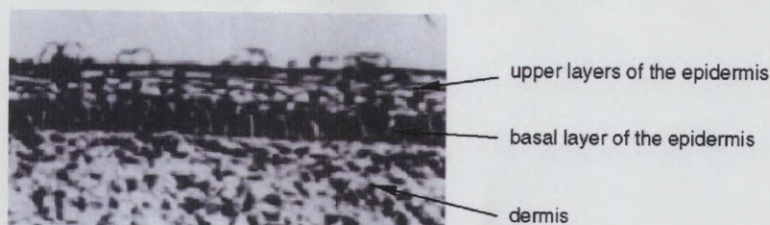


Fig. 1. Embryonal skin of the fingertip at the 10th week of pregnancy (from [8]).

identification mostly rely on statistical analysis because a mathematical model for the formation of these features is not available. Recently, the problem has been somewhat circumvented by efforts to produce realistic-looking fingerprints that can then be used for various purposes [2]. However, such simulations, no matter how realistic, provide no insight into the actual processes of fingerprint formation. Such insight could form a new approach for justifying the foundation of fingerprint evidence (especially concerning uniqueness), help to define measures of similarity, improve fingerprint recognition software and could be used to find quantitative measures of matching.

The path toward these goals is thorny. Biological phenomena such as the formation of fingerprints during embryogenesis are notoriously complicated and it is difficult to identify the crucial processes. Also, very often, important model parameters are unknown.

It is the purpose of this paper to review several mechanisms for fingerprint formation. Special focus is given to a model developed recently by the author and Newell [3–5]. Although this model uses advanced mathematical equations the basic ideas are quite simple and mathematical terminology will be avoided here. We will concentrate on the important concepts and not discuss all the subtle issues that came up during the modeling process [3,4].

The main topic of this paper is the physical mechanism for fingerprint formation. However, we also focus on the question how the direction of the ridges is determined and, connected to this topic, how the different pattern types (whorl, loop, arch) arise. In the first part of the paper we review the necessary biological material, some of which is not very well-known. In the second part we discuss the most important theories on fingerprint formation. Then we present our own ideas on the subject followed by a discussion and conclusions.

2. Biological background

The crucial events for human fingerprint formation start at the 10th week of pregnancy when the embryo has a size of just 80 mm. At that time embryonal skin already consists of two main parts: the epidermis sitting on top of the dermis. The epidermis is a typical epithelial tissue which is organized in several layers. The deepest layer on the interface to the dermis is called basal layer. The dermis of the 10th week has an amorphous appearance and consists of fibroblasts and collagen fibers (see Fig. 1) [6].

An important anatomical structure of the embryo's volar skin are the so-called volar pads. These are eminences of the volar surface at certain well-defined locations. They should not be confused with muscular eminences but rather consist of subcutaneous tissue and fat. In humans volar pads are found at the fingertips (apical pads), the distal part of the palm between the fingers (interdigital pads) and in the thenar and hypothenar areas (thenar and hypothenar pad), see Fig. 2.

In the human embryo, volar pads start to form at the 7th week of pregnancy. They continue to grow until about the 9th week and finally appear as high, rounded hillocks with a clearly defined base [7]. Later on they become smaller, appear less pronounced and their base merges with the surrounding tissue. Although apical and interdigital pads are still present in higher term embryos, and sometimes even at birth, the hand geometry eventually approaches the form of an adult. In human hands the hypothenar, the thenar and first interdigital pad are not well-developed and disappear early. On the foot the thenar pad merges with the first interdigital pad and forms what is called the hallucal pad, a large eminence below the base of the big toe. It is easily seen that areas that were covered by the embryonal volar pads are the sites where interesting patterns like whorls and loops appear, whereas, areas without pads usually exhibit

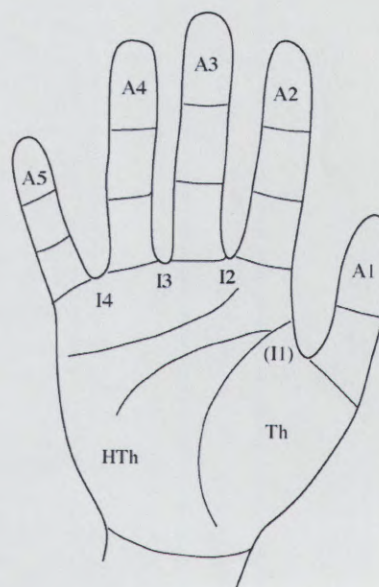


Fig. 2. The locations of the volar pads. A1–A5 denote the five apical pads on the fingertips. I1–I4 denote the interdigital pads. I1 is usually not well developed. Th denotes the thenar pad and HTh the hypothenar pad.