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Merkel cells and the individuality of friction ridge skin

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HIGHLIGHTS

- Model for the formation of epidermal ridge patterns using an agent-based model.
- Model links classical fingerprint literature with modern knowledge on Merkel cells.
- Agents are Merkel cells interacting in an anisotropic stress field.
- Pattern defects are sensitive to initial random Merkel cell distribution.

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ABSTRACT

There is no definite theory yet for the mechanism by which the pattern of epidermal ridges on fingers, palms and soles forming friction ridge skin (FRS) patterns is created. For a long time growth forces in the embryonal epidermis have been believed to be involved in FRS formation. More recent evidence suggests that Merkel cells play an important part in this process as well. Here we suggest a model for the formation of FRS patterns that links Merkel cells to the epidermal stress distribution. The Merkel cells are modeled as agents in an agent based model that move anisotropically where the anisotropy is created by the epidermal stress tensor. As a result ridge patterns are created with pattern defects as they occur in real FRS patterns. As a consequence we suggest why the topology of FRS patterns is indeed unique as the arrangement of pattern defects is sensitive to the initial configuration of Merkel cells.

1. Introduction

The goal of this paper is modeling the formation of friction ridge skin (FRS), which displays a pattern of epidermal ridges on fingers, palms and soles giving rise to what is popularly known as fingerprints. This pattern has great importance in forensic science and is increasingly used in biometric applications. The genetics and embryology of FRS patterns once attracted great interest as well and many different FRS traits were used for investigating patterns of heredity and diagnosing congenital diseases (Cummins and Midlo, 1976). But after the discovery of DNA the interest in the biology of FRS patterns markedly decreased. There is currently no model animal for FRS and no molecularbiological data on FRS development. This has led to the unusual situation that the most significant papers on FRS embryology are still the ones from the beginning of the 20th century.

The mechanisms for the development of FRS are still not completely elucidated and there is certainly no consensus yet how the pattern arises. However, there is an extensive literature that suggests that the pattern is formed as the result of a complex interaction of mechanical stress, trophic factors from incoming nerves and interactions between Merkel cells.

In this paper we will present a model for the interaction of Merkel cells and mechanical stress in the epidermis that results in a pattern of roughly parallel ridges. As a consequence of the model we discuss the role of genetic factors and why the topology of FRS patterns allows such a high level of discrimination between individuals. (Fig. 1).

2. Biological background

The pattern of epidermal ridges in humans is formed at around the 10th week of pregnancy at the interface of dermis and epidermis. It is observed that the basal layer of the epidermis becomes undulated forming what is called primary ridges (Bonnevie, 1927a; Babler, 1991; Hale, 1952). These primary ridges encode the pattern that becomes visible on the skin surface later on. Furthermore it is known that pattern formation does not take place simultaneously on the volar skin (Bonnevie, 1927a). Rather, the pattern first appears at the middle of the fingertip (close to the cores of loops and whorls) and around the nail furrow. A bit later it

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is formed around the proximal phalangeal crease. From these three places the pattern spreads over the entire fingertip and finally reaches the triradii, which are the locations on the fingertips where ridge formation concludes (see Fig. 2).

A very old strand in the literature links the direction of the ridges and the pattern type to the geometry of the volar pads. These structures are eminences of the volar fetal skin (especially at the fingertips and the distal part of the palm) that become prominent at about the 7th week of pregnancy and start to disappear at about the 10th week—the same time when the FRS pattern is formed. As been shown by many studies large, pronounced pads on the fingertips give rise to whorls, less pronounced pads give rise to loops and small pads give rise to arches (Babler, 1991; Cummins, 1926, 1929; Bonnevie, 1927b, 1932; Schlaginhaufen, 1905; Whipple, 1904).

For a long time these observations have been interpreted that growth forces due to differential growth are responsible for creating the pattern. Indeed, in images of developing patterns one can see that the unpatterned tissue already anticipates the direction of the pattern and stress lines seem to appear in the form of fine creases (see Fig. 2). Kücken and Newell (2004, 2005) hypothesized that there are two candidates for sources of growth stress. The first source originates from a larger growth rate of the epidermis whose expansion is resisted by creases and furrows creating compressive stress. The second source of compressive stress is the geometry change of the fingertips due to the receding volar pad. The stress distribution obtained by these two mechanisms can be calculated using finite element simulation. This way it is confirmed that the pattern type is linked to the volar pad geometry exactly in the observed way. Furthermore, by assuming that pattern formation would take place first in areas of large compression also the correct sequence of ridge spread over the fingertip is obtained.

This theory on the formation of growth stress outlined in Kücken and Newell (2004, 2005) is sufficient for understanding how the direction of the ridges might be determined but does not explain how a pattern of roughly parallel, almost equally distanced ridges arises.

There are many possible mechanisms that lead to the formation of a ridged pattern. In many cases these mechanisms are characterized by local self-activation and lateral inhibition such as in reaction–diffusion models. In these cases ridges are favored if the underlying equations have or lack certain symmetries, the self-activation has an upper limit or there are strong spatial anisotropies (Meinhardt, 1995; Koch and Meinhardt, 1994; Shoji et al., 2003). In our context the epidermal stress distribution is the prime candidate for anisotropies and is used as a guide for the ridge direction in the model presented below.

In Kücken and Newell (2004, 2005) it was assumed that the pattern was due to buckling of the basal layer, with the direction of the ridges following the lines of smallest stress. Although a large part of the classical literature implicitly hints at buckling as the pattern forming mechanism we point out that a mechanical instability without any biological feedback would be a rare process in the developmental biology. Furthermore, buckling would not be able to explain the formation of primary ridges of the observed depth—although it could be that the pattern arises first as shallow ridges can then be deepened by other processes.

In this paper we will incorporate a different strand of the literature in our model that is quite separated from the classical literature on FRS. This strand involves the most mysterious of all skin cells—the Merkel cell.

Merkel cells are epidermal cells that were first described by Merkel (1875). Until today they are difficult to study as they are hard to cultivate *in vitro*. Even basic questions regarding their embryological origin and their precursor cells are still controversial (Lucarz and Brand, 2007; Moll and Moll, 1992; Szeder et al., 2003). A part of this confusion may be due to different populations of Merkel cells that are colored by different dyes and different methods in detecting Merkel cells (Eispert et al., 2009).

In humans Merkel cells serve as a slowly adapting mechanosensor although the details of this function are still very much unclear (Haeberle and Lumpkin, 2008; Maricich et al., 2009). They are also conjectured to be able to detect electromagnetic radiation (Irmak, 2003, 2010). Furthermore, they influence tissue by a very large number of tissue hormones that they produce (Boulais, 2007). During embryology they are believed to serve as targets for innervating nerves towards the skin (Pasche et al., 1990). Merkel cells appear in the volar skin at about the 7th week of pregnancy and start to multiply. They are very likely to have an impact on FRS formation because around the 10th week of pregnancy they start organizing in lines exactly where the primary ridges arise

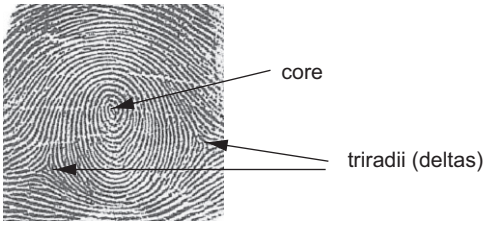

Fig. 1. An example for a whorl pattern at the fingertip. The pattern is characterized by a core area containing one or two singularities around which the ridges spiral and two triradii (also called deltas) where three patches of roughly parallel ridges meet.

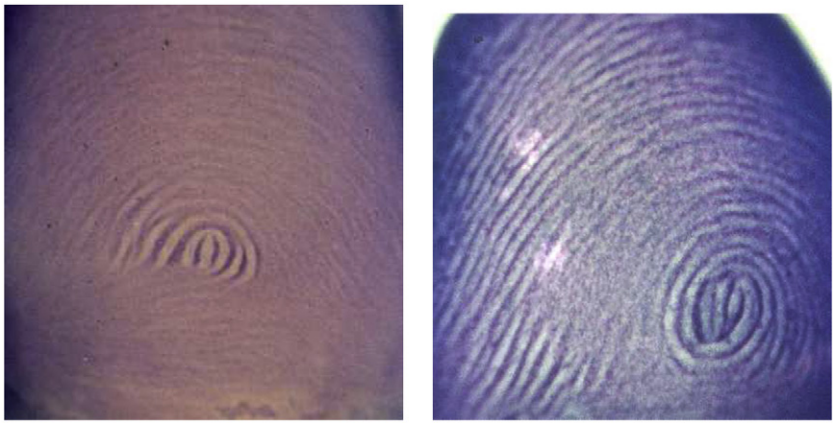

Fig. 2. Ridge formation on the fingertips starts in the core area, along the nail furrow and along the flexion creases. It concludes in the area of the triradii. (Courtesy of M. Okajima).