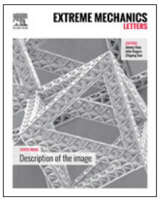
Extreme Mechanics Letters 9 (2016) 175–187

Contents lists available at ScienceDirect

Extreme Mechanics Letters

journal homepage: www.elsevier.com/locate/eml



Skin stretching by a balloon tissue expander: Interplay between contact mechanics and skin growth

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ARTICLE INFO

Article history:
Received 18 April 2016
Received in revised form 9 June 2016
Accepted 24 June 2016
Available online 4 July 2016

Keywords:
Membrane
Large deformation
Contact
Skin
Growth
Tissue expander

ABSTRACT

A contact mechanics model is developed to study the mechanical interaction between an elastomeric balloon expander and human skin. Through this interaction, we determine the amount of skin growth and its dependence on the applied load, geometry and elasticity as well as biological factors governing skin growth. For simplicity, we consider rectangular expanders where one of the dimensions is much longer than the other. This simplification allows us to obtain an analytical formulation which is valid for arbitrarily large deformation and contact. In this study, the balloon expander is modeled as an ideal rubber and we used a skin growth model where the growth rate is independent of the elastic stress in the skin. One of the advantages of our formulation is that it can be easily generalized to include more realistic constitutive models for skin growth and elastic behavior of the expander. Our method involves solving algebraic equations and thus is significantly simpler to implement than the commonly used Finite Element method.

1. Introduction

Reconstructive skin surgery using tissue expansion is a widely used in-situ technique for treating congenital defects, burn injuries and breast reconstruction. This technique is particularly useful as the new skin grown is similar in color, texture, thickness and hair growth characteristics [1]. This technique was first used 60 years ago for reconstruction of an ear defect as reported by Neumann [2]. Later it was used for breast reconstruction [3] and treating pediatric burn patients [4]. A broad overview of tissue expansion technology for pediatric patient treatment can be found in [1]. Fig. 1 shows the steps involved in a typical pediatric skin reconstruction for repairing congenital nevus on the patient's forehead [5]. The process involves placing multiple tissue expanders near the defect location between the dermis and hypodermis layers. These expanders are then inflated manually to a level that is typically decided in a subjective manner based on visual judgment or patient comfort [1,6,7]. This process is repeated multiple times over weeks until the required amount of new skin can be harvested. These expanders are empty silicone elastomer balloons that are non-porous and come with a remote injection dome [8].

A clear understanding of the mechanobiology of the skin, especially the coupling between the elastic (mechanical) and growth (biological) functions is imperative to the improvement of tissue expansion techniques. Human skin is a complicated multi-functional structure that performs a wide variety of important biological functions such as sensory input, protection and thermal regulation among others. Skin consists of three primary layers: epidermis (outer cellular layer), dermis (thick elastic inner layer) and hypodermis (base fatty layer) [9]. From the mechanical standpoint, the human skin behaves like an inhomogeneous, nonlinear, anisotropic and time dependent material

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http://dx.doi.org/10.1016/j.eml.2016.06.008
2352-4316/

Fig. 1. Pediatric tissue reconstruction using tissue expansion. The patient presented with a congenital nevus on the forehead. Tissue expanders were placed subcutaneously in the skin to grow the requisite amount of new skin that was then utilized to repair the defect. The new skin showed the same visual and hair growth characteristic as the surrounding skin [5]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

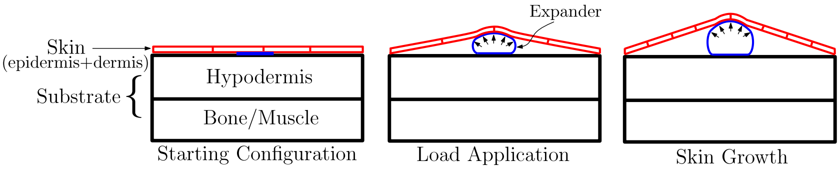

Fig. 2. Schematic of skin growth using tissue expander [16]. (Left) The unloaded expander (blue) is first inserted between substrate (hypodermis, shown in black) and the skin (epidermis and dermis, shown in red). (Center) The expander is then inflated almost instantaneously up to the requisite pressure or stretch ratio. (Right) The skin then grows to relax the stress. The segments drawn in the skin are indicative of the number of cells present. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

that has in vivo pre-stress and can undergo large deformations [10–13]. Additionally, skin undergoes growth to reduce stress when stretched beyond a certain limit. Specifically, a critical stretch activates a network of several integrated cascades involving cytoskeletal structure, growth factors, extracellular matrix, enzyme activity, second messenger systems and ion channel activity [9,14,15] leading to increased cellular growth and collagen synthesis which causes the skin to grow and restore the stress levels to homeostatic equilibrium (schematic shown in Fig. 2).

Tissue expansion involves the interplay of two key components: the mechanics of the skin-expander system and the growth dynamics of the skin. For example, for the same growth dynamics, the amount of skin growth in a given time frame depends on the geometry such as the thickness of expander and its elasticity as well as the history and manner of loading. Early models for the growth dynamics of skin are based on volumetric tissue growth kinematics which has been studied over the past many decades (see Taber [17] for a comprehensive review). More recently, analytical and computational continuum mechanics models describing volumetric tissue growth are developed by different investigators [18–31]. These continuum models have been used to study residual stresses and mechanical instabilities induced by tissue growth in thin structures such as plates and membranes [32–35]. Socci et al. [36] presented one of the first computational models for skin growth that was developed for axisymmetric geometries. Motivated by these studies, Tepole et al. [8,16] developed a more general 3D computational model that can be used to investigate skin growth for different expander shapes. Their method has the capability to simulate realistic scenarios like multiple expander pediatric reconstruction [37] and evaluating skin flap designs [38]. For a more comprehensive overview of the efforts and trends over the years in the study of mechanobiology of skin growth, the readers are directed to the review articles by Garikipati [39], Ambrosi et al. [40] and Kuhl [41].

Most works on skin growth have focused on the continuum mechanics and growth characteristics of the skin alone but to the best of our knowledge, there have been no efforts to include expander mechanics in the modeling and simulations. For example, Tepole et al. [8,16] assumed an infinitely compliant expander subjected to a constant pressure, so there is no air gap between the expander and the skin (100% contact); for this case there is no pressure drop across contact and the role of expander can be replaced by imposing a uniform pressure on the skin. In reality, *contact* between the skin and the expander as well as between the expander and the substrate is changing as the skin grows. The pressure acting on the skin is not the same as the air pressure inside the expander since there is a pressure drop across contact, which depends on the elasticity and geometry of the expander. Also, since the volume of the expander changes as the skin grows, the pressure inside the expander cannot possibly remain constant for a fixed amount of air. Thus, the elasticity of the expander, the contact condition and the way it is inflated can significantly affect the skin layer being expanded and its rate of growth. The uniform pressure model without contact mechanics (commonly used in existing works) neglects the