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THE VARIETY OF FACTORS THAT INFLUENCE THE BIOMECHANICAL PROPERTIES OF THE LIMB SKIN DURING LENGTHENING

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SUMMARY

The aim of this work is to analyze the influence of some factors on biomechanical behavior of the human skin in natural growth and in graduated lengthening with application of the Ilizarov fixator.

45 healthy individuals of various age and 104 patients suffering from congenital shortening of one lower limb or osteomyelitic sequelae have been examined. The limb discrepancy was eliminated by mono- and bilocal osteosynthesis with application of the Ilizarov fixator. The amount of lengthening comprised 3 - 14 cm, its relative value achieved 6 - 30%. Distraction started in 5 days following fixator placement.

Biomechanical parametres were determined with the help of the device designed by A.A. Utenkin. The method allows for studying skin deformation properties - shift stiffness (S, kg/mm^2) by minimal in time loading but constant in value moment, as well as for calculation of the amount of relative deformation (stretching, ξ, %). The work reports on the effect of different factors – structural and age ones, conditions of reparative lengthening and processes of regeneration – on the mechanical behavior of the limb skin in shortening of different etiology and gradual traction for equalizing limb length.

There is a number of factors having influence on the skin biomechanics of the human extremity: 1 - structural peculiarities of the collagen bundles and elastic fibres in the papillary and reticular dermis layers (collagenous fibres make up 98% of the connective dermis tissue and provide its high stiffness). The conformation principle of the collagenous and elastic fibrillas and fibres is their spiral character**.** 2 - the type of the collagen viscosity in the dermis, especially in its deep layers; 3 - age factor; 4 - an amount and etiology of limb shortening in patients with the locomotor system orthopaedic pathology; 5 - the method of limb shape modeling (lengthening and deformity correction) in the conditions of the guided transosseous osteosynthesis (mono- and bilocal osteosynthesis); 6 - skin regeneration (Ilizarov effect) as a consequence of the formogenetic effect appearing in the conditions of tension stress.

KEY WORDS: biomechanical behavior of the human skin, natural growth, graduated lengthening, Ilizarov fixator

INTRODUCTION

Human skin has a number of important functions. It covers the entire human body and defends the underlying tissues from injuries and impacts. Its total surface in an adult person comprises 1.5-2.0 square metres while its volume is 1/6th - 1/7th part from the entire body. The skin structure in humans has a particular difference from that of the animals caused by a phylogenetically conditioned upright human stature, absence of hair integument and social existence (Ye.V. Vinogradova, 1975). The human skin is also characterized by its lower mobility relevant to the underlying tissues and by a larger diameter of collagenous bundles in the transverse section (100-200 μm in a human and 30-40 μm in a pig).

When modelling the limb shape (lengthening and/or thickening) all the components of the segment under lengthening turn to the condition of tension and deformation. As previously stated, a successful surgical lengthening depends upon a stable osteosynthesis, low traumatism of the surgical intervention, a full blood supply, an optimal rate and frequency of distraction, preservation of the limb function. All these conditions have been mostly referred to bone regeneration while the influence of various factors on soft tissues, surrounding the lengthened bone, has been less intensively studied. And while definite success has been achieved in studying morphological parametres of soft tissues during limb lengthening in experiment on animals, the research of human limb soft tissue structural and functional reconstruction in vivo has been insufficient.

Functional and radioanatomical soft tissue changes during limb lengthening have been studied previously in achondroplastic patients and other orthopaedic pathology (5, 6, 17, 18). But some problems are still to be solved. It refers to the changes in biomechanical skin properties due to the patient's age. The difference in skin condition during various lengthening techniques has been also little studied.

The aim of this work is to analyze the influence of some factors on biomechanical behavior of the human skin in natural growth and in gradual lengthening with application of the Ilizarov fixator.

MATERIALS AND METHODS

45 healthy individuals of various age groups

and 104 patients suffering from congenital shortening of one lower limb or osteomyelitic sequelae have been examined. The limb discrepancy was eliminated by mono- and bilocal osteosynthesis with application of the Ilizarov fixator. The amount of lengthening comprised 3-14 cm, its relative value achieved 6 - 30%. Distraction started 5 days after the fixator placement (3).

Biomechanical parametres were determined with the help of the device designed by A.A. Utenkin (22). The method allows of studying skin deformation properties - shift stiffness (S, kg/mm^2*degree) by minimal in time loading but constant in value moment, as well as for calculation of the amount of relative deformation (stretching, ξ, %). The device has a small size (its working part in the shape of a ring is 28*20 mm). The maximal shift tension was 0.00840 MPa, the maximal rotational moment comprised 10.8 mm.

The studied skin area was located on the anteriorlateral surface in the middle tibial third. The patients were positioned horisontally, the knee joint angle counted 180D. The measurements were performed before surgery, during distraction and fixation, as well as 2-12 months after the lengthening completion.

RESULTS AND DISCUSSION

Age dependence of the limb skin deformation properties

The age dynamics of shift stiffness and amounts of relative deformation was followed for the humerus, forearm, femur and tibia in healthy individuals (9). The femur and tibia showed an exponential dependence between the values of the lower limb skin relative deformation and age:

Femur $\epsilon = 11.321 * e^{(-0.1733*T)}$ r = 0.46 P 0.05

Tibia $\epsilon = 3.0316\ e^{(-0.0693*T)}$ r = 0.51 P 0.05

ϵ - the value of a relative skin deformation or stretching (%), e - a base of a natural logarithm equal to 2.71, T - age in years. The other mechanical parametre is an amount of the skin shift stiffness that is determined according to the regression equation:

Femur S=0.0083* T+0.0192 r=0.62 P 0.01

Tibia S=0.0095* T+0.0412 r=0.44 P 0.05

(T is age in years). As it comes out of these relations, the index of relative deformation decreased with age while shift stiffness increased (10).

Morphological research data show that infantile skin is considerably thinner than an adult one (II). So, in babies the dermis is 1.5-2 times thinner than in adults but the subcutaneous fat cellular tissue differs little from its condition in an adult individual. The reported works (13, 14) mention that collageneous dermis fibres in early childhood consist of friable bundles that grow thicker and denser to the age of 10-12, they become much more twisted and interknitted. Dermis continues thickening up to the age of 16-30.

Light microscope investigation data testify that the fibrous structures of the skin in 5-9-year old children and adults are similar (15). The study of dermis elements ultrastructure of a normal infantile skin revealed some peculiar features as compared with adults (1). It refers to the structure of collagenous fibrillas, the width of their periods is less and comprises 450 – 500 Å. A large amount of fibrous material was discovered near collagenous and elastic fibres and testifies that fibrous substances are actively synthesized during childhood. Therefore, the age dynamics of biomechanical properties of human skin is determined by its various structural features. Mechanical properties of the skin in the limb segments are influenced greatly by the type of collagenous viscosity in the reticular dermis layer. As reported by some scientists, there are not only age but also topographic peculiarities in the skin structure. The location and relations of the collagen fibres have a great influence on the dermis deformation features (14).

On the whole, the viscosity type of the human limb skin is characterized by its layers; collagenous fibres are positioned in parallel layers; rigid or weak relations of the dermis collagenous frame with a subcutaneous cellular tissue or structural relations with fasciae are possible in various areas.

The dependence of collagenous fibres thickness on the depth of their positioning was also revealed. They are the thickest in the dermis reticular layer (24).

The surface of the collageneous bundles transversal section in the skin of young people is considerably less than in old subjects and comprises 0.4 mm^2 for the limb skin (16, 23, 24). As reported (23) the skin on the lateral tibial surface has additional bundles oriented almost perpendicularly or tangentially to the skin surface thus providing its greater stiffness and less stretching as compared with the medially located areas.

Our research (9), when shift stiffness absolute values were compared in the individuals of the same age, has revealed that the stiffness of the humerus and femur skin is considerably lower than the corresponding values in the forearm and tibia.

Thus, the regional difference in the skin relative deformation and elasticity is determined by the dermis structure and the type of the mutual interknitting of collageneous and elastic fibres, the epidermis structure and the boundary area between the epidermis and the dermis. The skin structure as well as underlying tissues play a decisive part in the process of skin relaxation (20).

In some diseases (desmogenesis imperfecta) the skin is easily torn which is caused by the insufficient development of the collagenous structures.

As it was reported in the literature the main structural components of the skin that take the mechanical loading are collagenous fibres that are well wound spirally (4). The conformation principle of the dermis collagen at various structural levels is its spiral character (14). The polypeptid chains and collagen macromoleculas are spiral, fibrillas are spiral too. Spiral orientation was revealed in the architechtonics of other tissues - muscular bundles, tendons, vessels' walls, dura mater and even in the long tubular bones (21).

According to many researchers the appearance of spiral structures, in long bones in particular, is caused by the effect of twisting that is revealed in the period of human phylo- and ontogenesis. According to Ph. Fouques the twisting of the musculus latissimus dorsi and musculus pectoralis major is found in the human embryo at early stages of its development while this phenomenon is not noted in animals (21, p. 130). Ph. Fouque associates this twisting with the upright human stature. Thus, spiral shape of the architechtonics is one of the principles in macrostructure organization; this refers also to the skin. The biological essence of the spiral shape of the skin structural components lies in the formation of the definite mechanical tissue properties, i.e. relative deformation, viscoelasticity and stiffness

Deformation properties of the skin during limb elongation. The biomechanical skin properties of the shortened tibia in patients with a congenital limb anomaly depend on the amount of shortening. Thus, the index of relative deformation of the shortened limb ξ (%) in the preoperative period had a nonlinear dependence from the anatomical limb length (L, cm):
$\xi = 0.8225 + 13.352\ e^{-0,159*L}$. Mathematical dependence of the skin shift stiffness S (kg/mm) from the anatomical tibial length L (cm) has been found:

$$S = 0.0013L + 0.0118 \quad r = 0.8225, \quad P< 0.05$$

In the other conditions the dependence of the deformation on the length of the skin sample was also nonlinear (7).

By the end of the graduated monolocal tibial lengthening a considerable decrease in the index of skin deformation in the operated segment was noted, that was II times less in children and 15.8 times less in adult patients (ξ = 0.05 - 0.6%). In 12-14 year old children the decrease in deformation properties of the tibial skin during distraction was less marked, which is probably caused by the growth leap in the puberty period. The possible explanation of the noted difference is a large reserve in the structural adaptation of the tissue, as well as its great regeneration potential.

The analysis of the mechanical properties in the tibial skin during lengthening at one or two levels (mono- and bilocal distraction osteosynthesis) showed the following features. When the tibia is lengthened to 4-11 cm the bionechanical behavior of the skin by mono- and bilocal osteosynthesis is similar: the shift stiffness grew 4 or 2.69 times correspondingly. The response of other soft tissues (muscles, blood vessels) to graduated lengthening by mono- and bilocal osteosynthesis also differed in achondroplastic patients (6, 17).

The process of tension stress dominates in limb lengthening, when definite distraction efforts are created in the system "fixator - extremity", that causes regular changes in the biomechanical behavior of the limb skin. The skin envelope of the operated segment transfers to a tensile and deforming (but oriented) condition. Once regeneration is completed relaxation develop. Subsequently, structural and functional skin properties corresponding to the new biomechanical conditions start forming in the tissues of the lengthened limb.

In conclusion, there is a number of factors which influence the skin biomechanics of the human extremity: I - structural peculiarities of the collagen bundles and elastic fibres in the papillary and reticular dennis layers (collagenous fibres make up 98% of the connective dermis tissue and provide its high stiffness). The conformation principle of the collagenous and elastic fibrillas and fibres is their spiral character. 2 - the type of the collagen viscosity in the dermis, especially in its deep layers; 3 - age factor; 4 - an amount and etiology of limb shortening in patients with the locomotor system orthopaedic pathology; 5 - the method of limb shape modelling (lengthening and deformity correction) in the conditions of the guided transosseous osteosynthesis (mono- and bilocal osteosynthesis); 6 - skin regeneration (Ilizarov effect) as a consequence of the formogenetic effect appearing in the conditions of tension stress.

The analysis of various factors that have influence on the limb skin biomechnical status is both of theoretic and practical value. It regards, first of all, the management of vast infected wounds in open bone fractures and bone loss with the application of the method of gradual tissue stretching (8, 12).

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ПРО ФАКТОРИ, ЯКІ ВПЛИВАЮТЬ НА БІОМЕХАНІЧНІ ВЛАСТИВОСТІ ШКІРИ КІНЦІВОК ПРИ ПОДОВЖЕННІ

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РЕЗЮМЕ

Мета роботи полягала у вивченні впливу деяких чинників на біомеханічну поведінку шкіри кінцівок у процесі природного зростання і дозованого розтягу за допомогою апарата Ілізарова. Обстежено 45 здорових людей різноманітного віку і 104 пацієнти з природженим укороченням однієї з нижніх кінцівок або з наслідками перенесеного остеомієліту. Подовження здійснювали за методом моно- і білокального остеосинтезу із застосуванням апарата Ілізарова. Термін подовження складав 3-14 см, відносне подовження – 6-30%. Дистракцію здійснювали на 5 день після накладення апарату.

Біомеханічні характеристики визначали за допомогою приладу А.А. Утенькіна, аналізуючи такі деформаційні параметри: зсунуту жорсткість (S, кгс/мм^2 град.) при постійній величині навантаження, що додається, і величину відносної деформації (ξ,%). У роботі описується вплив різноманітних чинників на біомеханічну поведінку укорочуваної кінцівки різноманітної етіології – структурних, фактора віку, виду методики подовження у процесі зрівнювання довжини кінцівки.

До таких чинників відносять: 1 - особливості будівлі колагенових пучків і еластичних волокон сосочкового і сітчатого шарів шкіри (колаген складає 98% єднальної тканини дерми і забезпечує її високу жорсткість). Конформаційним принципом будівлі колагенових пучків є їх спіралевидна звитість; 2 – тип колагенової в'язи в дермі, особливо в глибоких шарах; 3 – віковий чинник; 4 – величина і

етіологія укорочування у хворих з ортопедичною патологією; 5 – методика оперативного моделювання розмірів і форми кінцівки в умовах чрескосного остеосинтезу (моно - і білокальний остеосинтез); 6 – регенераторні процеси у шкірі сегменту, які подовжують кінцівки, як прояв «ефекту Ілізарова» в умовах напруги розтягу.

КЛЮЧОВІ СЛОВА: біомеханічна поведінка шкіри людини, природне зростання, дозований розтяг, апарат ІлІзарова, кінцівка

О ФАКТОРАХ, ВЛИЯЮЩИХ НА БИОМЕХАНИЧЕСКИЕ СВОЙСТВА КОЖИ КОНЕЧНОСТИ ПРИ УДЛИНЕНИИ

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РЕЗЮМЕ

Цель работы состояла в изучении влияния некоторых факторов на биомеханическое поведение кожи конечностей в процессе естественного роста и дозированного растяжения с помощью аппарата Илизарова. Обследовано 45 здоровых людей различного возраста и 104 пациента с врожденным укорочением одной из нижних конечностей или с последствиями перенесенного остеомиелита. Удлинение осуществляли по методике моно- и билокального остеосинтеза с применением аппарата Илизарова. Величина удлинения составляла 3-14 см, относительное удлинение – 6-30%. Дистракцию осуществляли на 5 день после наложения аппарата.

Биомеханические характеристики определяли с помощью устройства А.А. Утенькина. Анализировали следующие деформационные параметры: сдвиговую жесткость (S, кгс/мм^2 град.) при постоянной величине прилагаемой нагрузки и величину относительной деформации (ξ, %). В работе описывается влияние различных факторов на биомеханическое поведение укороченной конечности различной этиологии – структурных, фактора возраста, вида методики удлинения в процессе уравнивания длины конечности.

К таким факторам относятся: 1 - особенности строения коллагеновых пучков и эластических волокон сосочкового и сетчатого слоев кожи (коллаген составляет 98% соединительной ткани дермы и обеспечивает ее высокую жесткость). Конформационным принципом строения коллагеновых пучков является их спиралевидная извитость; 2 – тип коллагеновой вязи в дерме, особенно в глубоких слоях; 3 – возрастной фактор; 4 – величина и этиология укорочения у больных с ортопедической патологией; 5 – методика оперативного моделирования размеров и формы конечности в условиях чрескостного остеосинтеза (моно- и билокальный остеосинтез); 6 – регенераторные процессы в коже удлиняемого сегмента конечности как проявление «эффекта Илизарова» в условиях напряжения растяжения.

КЛЮЧЕВЫЕ СЛОВА: биомеханическое поведение кожи человека, естественный рост, дозированное растяжение, аппарат Илизарова, конечность