

Skin response to mechanical stress: Adaptation rather than breakdown—A review of the literature

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Abstract—The abnormal loading of skin and other surface tissues unaccustomed to bearing large mechanical forces occurs under many circumstances of chronic disease or disability. A result of abnormal loading is breakdown of the body wall tissues. An effective rehabilitation program avoids the pathological processes that result in skin trauma and breakdown and encourages load-tolerance and adaptation, changes in the body wall so that the tissues do not enter an irreversible degenerative pathological process. In the past, prevention has been the principal approach to the challenge of maintaining healthy skin and avoiding breakdown; therefore, relatively little is described in the rehabilitation literature about skin adaptation. However, adaptation has been investigated in other fields, particularly biomechanics and comparative anatomy. The purpose of this paper is to assemble the research to date to present the current understanding of skin response to mechanical stress, specifically addressing load cases applicable to rehabilitation. Factors important to tissue response are considered and their effects on adaptation and breakdown are discussed.

Key words: *adaptation, bedsores, decubitus, pressure sores, prevention, skin breakdown.*

INTRODUCTION

One of the common manifestations of chronic disease and disability is the abnormal loading of

skin and other surface tissues unaccustomed to bearing large mechanical forces. There are many general etiologies, including paralysis, altered sensation, altered level of consciousness, prolonged bedrest and sitting, and the use of an orthosis or prosthesis.

A result of abnormal mechanical loading of surface tissues is breakdown. Though breakdown might appear initially as only a slight reddening of the skin, it can develop into a significant injury that damages tissues through the entire thickness of the body wall. Changes in color of the skin, blisters, bruises, and excoriations often develop and are signs of early breakdown. If loading continues unchanged in an area that demonstrates early breakdown, irreversible injury and necrosis might occur. More extensive pressure ulcers develop which extend deeper into subcutaneous tissues, sometimes into joint or body cavities. Typically, these more extensive ulcers require debridement of necrotic tissues followed by prolonged periods of pressure relief. Both conservative and surgical treatment programs are then employed to debride the pressure ulcer and allow healing of tissues.

The principal approach in the past to the challenge of maintaining healthy skin and avoiding breakdown has been prevention. For example, patients restricted to bedrest, a subject population at high risk of pressure ulcer formation, will be turned frequently by the nursing staff to relieve prolonged pressure. Mattresses designed to cyclically change the distribution of pressure have been developed.

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Similarly, custom-designed wheelchair cushions are manufactured to help distribute the load more evenly. Further, patients in wheelchairs are taught to conduct pressure releases regularly to prevent breakdown. Patients with altered sensation use timers to indicate when pressure releases should be conducted, and they undergo extensive educational programs to encourage effective prevention practices. For patients with limb deficiencies, orthoses and prostheses are custom-designed so as to distribute forces properly at the body support interface in a manner that avoids skin breakdown. Thus, current prevention programs are designed to reduce force levels and loading durations below those that cause breakdown.

Ideally, tissue pressure management and prevention programs would eliminate all skin breakdown. However, attempting to reduce force levels and durations conflicts with life and functional activities. Mechanical forces and/or load durations are now induced in regions that do not typically bear such high loads. For example, in spinal cord injury (SCI) patients, the sacral and ischial regions are subjected to large pressures during sitting. Persons with below-knee amputation will typically expose the antero-distal regions of their residual limbs to excessive normal and shear stresses due to interaction with the prosthetic socket during ambulation. It is important to recognize that the load levels are much higher than those typically borne by the tissues at these sites. Frequently, breakdown occurs, particularly during the early weightbearing period, and results in increased costs, prolonged hospitalization, increased morbidity and mortality, lost time at work and home, and psychological trauma.

Scope and Cost of Skin Breakdown. The scope and cost of skin breakdown in the US are staggering. Research studies show a prevalence of decubitus ulcers in 11 percent of the hospitalized population and in 20 percent of nursing home residents at any given time (1). For patients in nursing homes, the prevalence of pressure sores (of Grade 2 or greater) ranges from 7 to 35 percent (2), resulting in a four-fold increase in mortality (3). In SCI patients, pressure ulcer incidence is as high as 42 to 85 percent in some centers (4). Amputees using prosthetic limbs are also at risk of breakdown, as a result of the mechanical forces at the residual limb-socket interface. Over 43,000 new major amputations are performed per year in the US (5), with 58 percent of

them on patients between the ages of 21 and 65 years (trauma, cancer, congenital). Thus, there is a significant patient population of young people with amputation, a group likely to conduct strenuous activities when using their prosthetic limbs. For those persons with amputation over 50 years old, vascular causes are the etiology in 89 percent of the cases (6). Their skin is typically at high risk of breakdown.

From a financial standpoint, direct medical expenses associated with curing skin that has broken down are tremendous. As an example, the "average" cost of pressure sore treatment was \$120,000 per sore in 1987 (7). Total costs for treating pressure sores in the US, including medical and surgical care, hospital bed occupancy, lost time from work, nursing home care, home health care, special equipment, and transportation, are estimated to exceed \$3-\$7 billion per year (8). Thus, it is clear that skin breakdown induces much hardship and expense, and treatments to avoid breakdown are needed.

Adaptation. Individuals with a chronic disease or disability frequently have conditions that affect body position and mobility. Abnormal loads in areas that are not primarily designed for weight-bearing are encountered in these individuals. Therefore, maintenance of skin integrity is one of the primary goals following the onset of a severe disabling condition.

Rehabilitation programs typically focus on prevention and education to avoid the pathological processes that result in skin breakdown. Prevention measures involve the application of interface surfaces (mattresses, cushions, liners) and frequent pressure reliefs to avoid sustained pressures in one position. It is interesting to note that skin and body wall tolerance for sustained pressures typically increases over time (9). Perhaps effective treatment is not exclusively a matter of prevention, reducing the force levels and durations, but also a matter of adaptation or changing of the tissue itself. It is desirable to induce a rehabilitation process that involves adaptation of tissues rather than merely preventing breakdown.

Clinical treatments designed specifically to encourage skin adaptation and avoid breakdown do exist (10-12). A mobilization program for an individual with SCI who has undergone myocutaneous flap surgery for a pressure sore is an excellent example. Postoperatively, the surgical area is not

stressed for approximately 3 weeks. During this period, there is no weightbearing and no range of motion so as to avoid compression and tension on the flap. Subsequently, a typical program might involve several short periods of weightbearing while in bed. The duration of each period will be increased each day after successful completion of the previous day's program. Range of motion and progressive tensile forces will be placed on the surgical region during this same period of time. Finally, a sitting program will begin that also involves progressive increase in weightbearing duration.

Though some clinical treatments designed to encourage adaptation exist, numerous basic and clinical questions remain. How dependent are adaptive changes in the body wall to the magnitude and duration of the applied load? Is response dependent on the direction of the stress, for example, whether pressure, shear, or tension? Without answers to these questions, rational interventions to prevent breakdown and stimulation of adaptation will remain limited.

There is a growing body of biomechanical and comparative anatomical literature that clarifies some of the confounding issues in this area. The purpose of this paper is to review that literature, particularly information addressing skin adaptation to mechanical stress. Factors important to tissue response are considered and their effects on adaptation and breakdown discussed.

Adaptation involves the entire body wall, including loose connective tissue, fat, fascia, and muscle in addition to skin. In this paper, however, we have concentrated on skin and underlying tissue adaptation to mechanical stress, since skin is the most dynamic tissue of the body wall and offers great adaptation potential.

Functional Anatomy of the Body Wall

A presentation of the functional anatomy of the skin and underlying tissue is required for the reader who is less familiar with the anatomy of the body wall. A cross section of skin, with important components labeled, is shown in **Figure 1**. Skin is composed of two principal layers, the epidermis and the dermis, joined by a distinct structure, the dermal-epidermal junction.

The *epidermis*, the outermost and nonvascular layer of the skin, is a cellular layer that varies in

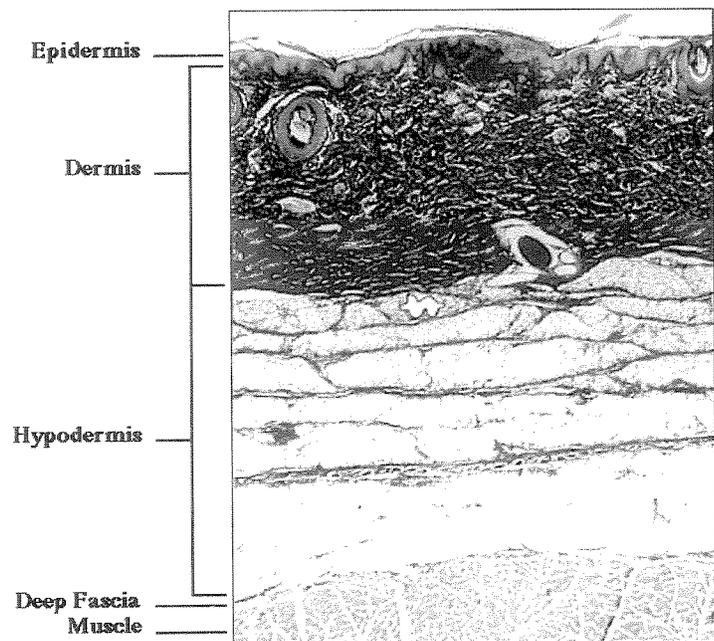


Figure 1.
A cross section of pig skin showing the different layers.

thickness from 0.07 mm to 0.12 mm, except on the palms and soles, where it varies from 0.8 mm to 1.4 mm (13). The epidermis serves to protect against physical and ultraviolet injury, to provide a relatively impermeable barrier to water and chemicals, and to establish a first line of resistance to microbial penetration.

The turnover of the epidermis contributes to the maintenance of its mechanical tolerance. Turnover is achieved by migration of the cells from their origin at the basement membrane, at the separation between the epidermis and dermis, toward the skin surface; this process takes approximately 28 days. As they migrate, cells die, lose their nuclei, and become more pancake-shaped with larger diameters but thinner cross sections, such that the surface area of a cell at the most external layer of the epidermis, the stratum corneum, is approximately 25 times that of one at the basement membrane.

As the cells migrate from the base to the surface of the epidermis, the process of keratinization (the synthesis and deposition of a specific fibrous scleroprotein, keratin, that fills the cytoplasm of the epithelial cells) occurs. Eventually, the epithelial cells die and only the keratin remains. During this process, the keratin molecules are reinforced by

formation of several disulfide bonds. This results in a layer of keratin molecules that are strong, insoluble, and resistant to enzymes and breakdown.

Attachments between cells contribute to the mechanical strength of the epidermis, and they are achieved via the desmosomes (bipartite structures consisting of plaque-like local differentiations on the surfaces of opposing cell membranes). A feltwork of fine filaments spans the gap between the plaques of the two cells. Tonofilaments in the cytoplasm converge on the desmosomal plaque; thus, desmosomes also serve as sites of attachment of the cytoskeleton to the cell surface.

The *dermal-epidermal junction* (DEJ) is an important interface of mechanical attachment between these two distinctly different layers of the skin: the epidermis and the dermis. It is composed of a basement membrane that is wavy in shape with finger-like projections that extend into the dermis. Anchoring filaments (type VII collagen) extend from the dermal side of the basement membrane to plaques (types IV and VII collagen) within the papillary dermis. It has been proposed that attachment of the basement membrane with the underlying collagen fiber matrix (types I and III collagen) is achieved via intertwining of the collagen fibers with the network created by the anchoring filaments and plaques (14).

The DEJ has at least three major functions: it provides a permeable barrier between the vascular dermis and the avascular epidermis; it provides contact between the epidermal cells and the macromolecules within the DEJ, which contact is thought to influence the epidermal cells during their differentiation, growth, and repair; and the DEJ is important for adherence of the epidermis to the underlying tissues. The major point of weakness of the DEJ is considered to be its sublayer, the lamina lucida (15).

The *dermis* is the connective tissue matrix of the skin, providing structural strength, storing water, and interacting with the epidermis. In humans, dermal thickness varies from 1 mm to 3 mm. Its principal components include elastin (0.2 to 0.6 percent by volume; 4 percent by dry weight), collagen (27 to 39 percent by volume; 75 to 80 percent by dry weight), glycosaminoglycans (0.03 to 0.35 percent by volume), water (60 to 72 percent by volume), and cells. Each component has important functions.

Elastin is a fibrous protein that forms a meshlike network in skin. It gives skin its mechanical integrity at low loads, as demonstrated by elastin degradation that causes skin to lose its recoil capability at low force levels (16). Fiber diameters of elastin are approximately 1–3 μm . Each elastin fiber is made up of microfibrils of 10–12 nm diameter. Elastin is produced by fibroblasts.

Collagen is the principal fibrous load-bearing component in skin and provides mechanical integrity at higher load levels. Collagen fiber diameters range from 2–15 μm in skin. Fibers are made up of fibrils, which themselves are approximately 20–100 nm in diameter. Collagen molecules within the fibrils are arranged in a staggered array such that there is a 1/4 length overlap between adjacent molecules, a structure which gives fibrils a striated appearance under the electron microscope. Attachments between collagen molecules are achieved via crosslinks, covalent bonds between lysine residues of constituent collagen molecules. Collagen production involves fibroblast cells.

Collagen remodeling occurs in normal skin, during stress, in pathologic situations, and during wound healing. This remodeling is dependent upon the shifting equilibrium of collagen synthesis and collagen catabolism. The degradation of collagen is initiated by several collagenase enzymes secreted by fibroblasts, epidermal cells, and granulocytes. The enzyme collagenase is representative of a group of connective tissue metalloproteinases responsible for collagen breakdown. Conversely, tissue inhibitors of the metalloproteinases (TIMP) exist. These macromolecules are thought to regulate collagen breakdown (17).

Evidence is accumulating that there is altered skin collagen synthesis and metabolism following SCI. There is evidence that there are qualitative and quantitative changes in skin collagen below the level of injury and as a function of time post-injury (18–21).

Glycosaminoglycans, principally dermatan sulfate, hyaluronic acid, and chondroitin sulfate make up the ground substance surrounding the fibrous components and, with water, contribute to the viscoelastic nature of skin. Glycosaminoglycans are covalently linked to peptide chains to form high-molecular-weight complexes called proteoglycans.

Cells within the dermis include fibroblasts, macrophages, mast cells, and leukocytes. Fibro-

blasts are the principal cells responsible for the creation of collagen, elastin, and glycosaminoglycans. Fibroblasts also play a role in wound healing in that they help to align collagen fibrils with the direction of principal mechanical stress, contributing to closure and strengthening of a healing wound (22).

The vasculature of human skin is composed of two distinct parts, the nutritional capillaries and the thermoregulatory blood vessels. The nutritional capillaries are organized into vertical capillary loops in the papillary dermis, providing nutrients to the upper dermis and basement membrane. The thermoregulatory vessels are larger, deeper vessels that run parallel with the skin surface, assisting in heat transfer to and from the skin.

Subcutaneous Tissue. The skin is connected to the underlying bones or deep fascia by a layer of areolar tissue that varies widely in character in different sites and between species. This layer is well developed in humans and has been named subcutaneous tissue, superficial fascia, or panniculus adiposus.

The limbs and body wall are wrapped in a tough membrane of fibrous tissue called the deep fascia. It varies widely in thickness, although in general it is arranged as an irregular, dense, collagenous, relatively avascular network. The deep fascia serves for attachment of the skin by way of fibrous strands in the subcutaneous tissue. In most areas of the body, underlying muscles are free to glide beneath the deep fascia.

The underlying muscular layer of the body wall consists of skeletal muscles bound together by loose areolar tissues and tougher connective tissue sheaths. The membranous envelope surrounding the entire muscle, the epimysium, is tougher in composition and resembles deep fascia; whereas the delicate endomysium between the individual muscle cells is composed of loose, vascular connective tissues. Muscle tissue is an extremely well-vascularized, aerobic tissue composed of parallel, non-branching striated muscle cells.

Evolutionary and Developmental Adaptation

A correlation between the structural design and mechanical demands in skin is suggested in the evolutionary and developmental literature. The observations are important because they demonstrate

changes in structure to sustain high magnitude or prolonged mechanical loads. There are two excellent reviews on the subject (23,24).

Several important findings have been made regarding this correlation.

- Collagen fibers in altricial animals have the same limiting diameter at birth and recommence growth after birth, probably as a consequence of postnatal exercise (24). In contrast, precocious animals, capable of locomotion immediately after birth, contain collagen fibrils which are sufficiently developed at birth to withstand the applied mechanical stresses. The form of the collagen fibril diameter distribution of tendon at birth reflects the degree of development of the animal at this stage of life.
- The ultimate tensile strengths of connective tissues and skin are positively correlated with the mass-average diameter of the collagen fibrils (25).
- Collagen fibril diameter distributions are a function of both the applied stress and its duration. The mechanical properties of a connective tissue are strongly correlated with the collagen fibril diameter distribution (24,26). In general, those skins subjected to increased tensional loads (rat tail skin, trout skin, dorsal skins of mammals) contain collagen fibrils of larger diameter than those skins with lower tension. Collagen fibril diameters were smallest in those skins bearing compression. For example, in guinea pigs fibril diameters were twice as large on the dorsum, a region subjected to tension, than were those of the footpad, a region subjected to high compression or pressure.
- Mammalian and avian body skins generally contain relatively sharp unimodal distributions of fibril diameters consistent with a "passive" mechanical role. Whereas reptilian and fish skins have bimodal distributions of fibril diameters compatible with an "active" biomechanical role typical of those animals with extensible skin attributes (26).
- The mechanical properties of a connective tissue are strongly correlated with the type and amount of glycosaminoglycans (23). This positive correlation exists in comparing skins from different sites within an animal, in comparing different species, and in comparing skins at various stages of development (23,27). For example, in altricial animals, there is a greater content of hyaluronic acid, a proteoglycan functionally designed for its hydrophilic properties but not particularly strong. In precocial animals,

their more mature skins at birth contain a greater proportion of sulfated proteoglycans (keratin sulfate), glycosaminoglycans designed to withstand greater mechanical forces.

To summarize: it is possible to make reasonable predictions about the type of force to which connective tissues are subjected by examination of the morphological and biochemical features of 1) the glycosaminoglycan composition and content; 2) the collagen fibril diameter distribution and the mode of packing; 3) the histological staining reaction of the collagen fibers by the Masson trichrome stain; and 4) the axial periodicity of the collagen fibrils (23,24,26).

Short-term Response To Mechanical Stress

The evolutionary relationships between structure and function described above suggest that continual loading induces structural changes in skin that improve load-tolerance. In the short-term, it is also desirable to encourage adaptive changes that increase load-tolerance. However, in the short-term it is also desirable to avoid degradatory processes that result in skin breakdown. Both breakdown and adaptation of skin to mechanical stress are addressed below. The literature on the topic can be divided by loading configuration: pressure, shear and friction, and tension.

Pressure. Pressure is a uniformly distributed force applied perpendicular to the skin surface. The effect of prolonged pressure on the skin of weight-bearing areas has been hypothesized as a major pathophysiologic factor in the development of pressure ulcers. Numerous animal studies and measurements in humans have been conducted in an attempt to demonstrate a pressure-time relationship for skin breakdown (animals: 28–32; humans: 33–36). Most of these investigations discuss the generally accepted model of pressure-induced ischemia leading to tissue necrosis.

In the animal models, external loads were applied to the skin and the tissue response assessed. Various outcomes have been measured including erythema, inflammation, reversible damage, irreversible breakdown, alterations in blood flow, transcutaneous oxygen tension, and temperature, to name a few. Different tissues of the body wall (i.e., epidermis, dermis, subcutaneous layer, and muscle) have been examined. Dinsdale (37), for example, applied

pressures from 45 to 1500 mmHg (6 kPa to 195 kPa) in normal and paraplegic swine for various durations and examined pathomorphological changes over time. He demonstrated epidermal and dermal alterations that preceded pressure ulcers, particularly at higher pressures for longer durations. Husain (32) demonstrated ischemic histologic changes in underlying muscles at 100 mmHg (13 kPa) for 2 hours. Complete muscle necrosis was demonstrated at 100 mmHg (13 kPa) for 6 hours. The changes included venous sludging, venous thrombosis, edema, cellular extravasation, decrease or loss of muscle striations, hyalinization of fibers, neutrophilic infiltration, and phagocytosis by neutrophils and macrophages. Kosiak (31) demonstrated that pressures of 70 mmHg (9 kPa) for 2 hours resulted in pathologic changes within muscle and that lower pressures of 35 mmHg (5 kPa) for 4 hours resulted in no changes. A clinically accepted relationship between pressure and duration, particularly over bony prominences, has been accepted (38).

The results suggest an important concept. Application of pressures for low or moderate durations is acceptable for intact skin. Damage might occur but is reversible. An equilibrium between breakdown and regeneration is established. Beyond a certain period of time or level of force, however, catabolic processes overcome reparative mechanisms and the net result is tissue breakdown. Thus, attention should be paid to the pressure-time relationship for skin breakdown, and threshold values for pressure and time at which injury occurs should not be exceeded.

A second important concept that has emerged from the research in animal models is that deeper tissues are more vulnerable to injury than skin. Daniel, et al. (28), Groth (29), and Nola and Vistnes (39) all demonstrated the earliest pathologic changes in muscle: with increasing pressure, ulceration progressed in a superficial manner toward the skin.

The pressure-duration relationship is affected by a multitude of intrinsic and extrinsic factors. Moisture, for example, places skin at greater risk for breakdown. A suggested explanation comes from the biomechanics literature. The stiffnesses of both the stratum corneum and the dermis decrease with increased humidity and temperature (40–42) probably because of a reduced load-supporting contribution from the stratum corneum in the epidermis and the glycosaminoglycans in the dermis. The skin

undergoes greater elongation, requiring the collagen to undergo greater strain, and possibly putting cells and the vasculature interspersed among the collagen fibers under greater concentrated stresses and risk of trauma.

Aging, smoking, and immobility are also important factors affecting the pressure-duration relationship (43,44). The thickness of skin decreases with age (45,46). As a result of a reduction in elastin, the elastic range of the skin is decreased. Collagen, proteoglycan, and water content, as well as blood supply, have all been shown to decrease with age, indicating a general atrophy of the body wall. Smoking is also an important risk factor for skin breakdown and is suggested to be related to decreased blood supply to the skin. Immobility results in prolonged pressure over bony prominences and this places an individual at high risk for skin breakdown. Paralysis combines immobility with muscle atrophy. Part of the problem is that the loss of sensation causes the individual to load the skin for extended periods of time without performing pressure reliefs regularly. However, neurogenic skin is also thinner than normal, indicating that a loss of constituents, possibly those important to load-tolerance discussed above, has occurred.

The location of the applied pressure on the skin relative to underlying bone has also been shown clinically to be relevant to the pressure-time relationship. Individuals who are supine in bed for prolonged periods typically break down over the occiput, scapulae, sacrum, and heels; whereas, an individual side-lying will break down over the greater trochanter and the malleoli. If sitting for prolonged periods, such as following a SCI, breakdown typically occurs over bony prominences (i.e., the ischial tuberosity and the sacrum). Persons with below-knee amputation commonly experience problems over the anterior residual limb surface, where skin is directly over bone, as opposed to posteriorly, where there is a thick layer of subcutaneous tissue and muscle. The high sensitivity of skin over bony prominences is explained mechanically. Stresses are concentrated in a very small connective tissue region between the bone and the surface; thus, high stresses and stress gradients, which threaten skin viability, occur. The threshold for injury is thus lower at thin skin sites over bone, and excessive loading should be avoided.

There is evidence that suggests skin can adapt if proper clinical treatments are conducted. Clinical practices dictate some loose rules for adaptation to loading under pressure (10-12). A good example is postsurgical treatment for a myocutaneous flap that has been transferred from an area that did not have much weightbearing. Inspection and palpation are the principal diagnostic tests used to evaluate the progression of skin adaptation. Inspection includes an assessment of erythema, detection of visible open wounds in the skin, and identification of ischemic changes. Palpation allows assessment of edema, and fluid collection in deep tissue layers. The SCI patient will initially lie on the affected region for short periods. If skin redness quickly disappears upon unloading, then another loading period will be conducted. If skin redness persists, then the site will be rested. Bogginess and pitted tissue are likely indicators of tissue breakdown beginning beneath the skin surface. The goal in postoperative treatment of a myocutaneous flap is for continuous sitting from morning until evening with pressure releases several times each hour.

Though descriptions for the early signs of skin breakdown (bogginess, fluid regions) are noted, clinical evaluation for signs of skin adaptation are lacking. Animal studies from the literature, however, provide some insight into structural changes that take place in skin subjected to repeated compression. Though no studies have been reported on skin, studies on tendon do exist. Tendon is a tissue made up of the same types of collagen and glycosaminoglycans as found in skin. In tendon previously under tension but then subjected to pressure, increases in glycosaminoglycan content during remodeling occur (47). In particular, hyaluronic acid and chondroitin sulfate content were found to increase. When tension was restored, the hyaluronic acid and chondroitin sulfate contents returned to normal values. These findings are consistent with the evolutionary changes described above for skin, though changes described in the tendon studied occurred over a relatively short time period. Thus, the literature suggests increases in hyaluronic acid and chondroitin sulfate are indicative of skin adaptation to pressure. Clinically, these changes might be apparent as a change in skin mechanical properties which possibly could be perceived during palpation assessment.

Shear and Friction. Shear stress occurs when a force is applied in the plane of the skin surface. Friction occurs when there is displacement between the skin and the supporting surface. For example, a patient with SCI who tilts up in bed from a supine position induces shear stresses in the sacral region over the bone. When there is slip between the skin and the bed, friction is induced. Persons using prosthetic limbs experience shear stresses at the residual limb-socket interface because the socket is designed to bear much of the weight on the sides of the residual limb rather than distally. "Pistoning," displacement of the residual limb relative to the socket, causes frictional loads.

The importance of avoiding shear stress in SCI patients has been addressed. Inducing shear stress at thin skin sites over bone will put excessive tension in the skin, increasing the risk of injury compared with the no-shear case. Effects on blood flow occlusion have been demonstrated. Bennett developed an apparatus to measure the applied pressure, shear, and pulsatile arteriolar blood flow on the palm of the hand near the thumb of human subjects (48). Results showed that at a sufficiently high level of shear, the pressure necessary to produce occlusion was half that required when little shear was present.

A number of clinical and animal studies have been conducted in an attempt to establish a load-time relationship for the threshold of breakdown from frictional stress. Naylor conducted systematic studies of blister formation in response to friction. A machine was used to rub the skin on the anterior tibial surface at a constant speed and with constant perpendicular force, and the frictional forces were recorded (49). Naylor utilized multiple loading regimes with various materials to quantify thresholds of blister formation. He investigated the work needed to produce a blister, defined as the product of the frictional force and the number of rubs. Results on human subjects demonstrated that the lower the frictional force, the greater the amount of work required to rupture the epidermis. In other words, given the choice of receiving a high number of rubs at a low force or a low number of rubs at a high force, the skin is more tolerant of the case of a high number of rubs under low force. Changes in material of the loading head, speed of rubbing, and dermal perfusion did not appear to alter the number

of rubs required to produce a blister. Sulzberger, et al. (50) also used a machine to rub the skin, and found a large variation among sites in the work required to produce blisters when the frictional forces were low. It was demonstrated that less time and work were required to produce a blister over thin skin than thick skin, an expected result because of the adapted load-tolerant structure of thick skin. Blisters form more quickly if the skin is heated rather than cooled (51). The frictional force on the skin depends on the amount of moisture at the skin surface. A small amount of water on the skin surface increases the frictional force compared with a dry surface. A large amount of water on the surface decreases the frictional force compared with a dry surface (52).

The above findings are important because they suggest rules for clinical practice. Given a choice of inducing a high force at a low repetition rate rather than a low force at a high repetition rate, the latter should be chosen. For example, an amputee walking up a flight of stairs would put skin at lower risk if he or she were to take one stride per stair rather than one stride per two stairs. A further suggested rule for clinical practice deduced from the shear force literature described above is that a small amount of sweat at the interface will increase frictional forces and increase susceptibility to breakdown. Thus, individuals that sweat often should take precautions to remove the sweat layer frequently or wear materials that absorb sweat well. In addition, if possible, frictional forces should be applied to thick skin sites instead of thin skin locations. Thus, skin structure should be inspected clinically to determine potential regions for load tolerance.

Other researchers have identified important parameters that affect the magnitude of the frictional force at the interface: relevant work because of the significance of force magnitude to tissue response as demonstrated in Naylor's studies described above. Interface materials have been studied by Jagoda, et al. (53), who compared blister formation in a group of Marines in training using different combinations of socks and powders. A green military issue sock worn over a white athletic sock was more effective at preventing blisters than a green issue sock alone or an athletic sock over a nylon sock.

Jagoda found other interesting results. The likelihood of blister formation depended on the running habits of the individual. Those who normally ran more than 30 miles per week were less likely to develop blisters than those who ran less than 10 miles per week, suggesting an adaptive response of the skin on the feet to continual running. In addition, incidence of blisters was highest in the early stages of training, indicating that adaptive changes took time to occur.

Histologically, examination of skin that has broken down under friction has been conducted. A mechanical system to apply an approximately constant normal force and a cyclic shear force to the skin surface was used (49,50). Rubbing was conducted until breakdown occurred. Results demonstrated that friction blisters occurred within the epidermis, as a result of shearing between the epidermis and deeper anchored layers, which creates a zone of damage or cleavage (50). In response to repeated rubbing, the skin becomes red, there is slight flaking of the stratum corneum, and finally the epidermis ruptures suddenly, producing sharp pain and a crater in the skin. Histologically, necrosis of prickle cells, formation of small intra-epidermal vesicles which coalesce to form larger vesicles, and edema in the dermis around blood vessels are observed (49).

The response, blister or abrasion, depends on the structure of the skin and its location on the body. Blister formation requires firm attachment to tissues below and a tough superficial layer. Differential movement of upper layers over lower ones produces shearing which results in a cleft that fills with fluid (54). The tear or cleft appears consistently at the same area in the epidermis: below the granular layer, or stratum granulosum, and above the basal layer, or stratum spinosum (53). Application of a tourniquet or elevation of the loaded region relative to the heart eliminates filling of the blister but the cleft still appears. Friction blisters generally occur only on the palms and soles where the overlying stratum corneum is thick enough to form a roof on the blister. On thinner skin, friction results in an abrasion rather than a fluid-filled pocket. In response to high friction levels, blister formation can occur in several minutes (acute response). If friction levels are below a certain threshold, adaptive thickening of the skin (epidermal hypertrophy) results instead of injury, and

thickening can increase over the course of weeks to months (chronic response).

Adaptation to shear can occur and is encouraged clinically. An ambulation protocol for a person with lower limb amputation is an example. Although the timing of postoperative weightbearing varies among practitioners and patients, increasing weightbearing begins very early postoperatively. Gentle weightbearing might begin as early as 1-2 days postoperatively to stimulate wound healing and begin proprioceptive feedback. The program then progresses with longer durations and increased forces during weightbearing activities. Activities progress through the following stages, progressively stressing the residual limb: gentle touch weightbearing, weight shifting, walking in parallel bars, ambulating with adaptive aids, and finally ambulating without adaptive aids.

An adaptive response to frictional loading is the formation of calluses. Calluses are even thickenings of the keratinized layer of the epidermis which form in response to repeated frictional loads. There is much variability in individual response, with some people tending to blister in response to slight friction, while others immediately develop a callus (55). Damp skin tends to blister, while dry skin tends to develop callosities. An explanation is that the damp skin produces higher friction, above the breakdown threshold for the skin compared with frictional forces induced in dry skin. Thickening of the horny layer, the outermost layer of the epidermis, has been observed in response to ultraviolet light, mechanical, chemical, electrical, and thermal stimulation (56,57).

Other epidermal adaptation studies to friction have been conducted to investigate the processes underlying the epidermal hypertrophy described above and the time course of the response. In mouse ears subjected to frictional loading by a rotating brush, increases in epidermal thickness, mitotic activity, cell sizes, and cell numbers were demonstrated (58,59). The rate of migration of cells from the basement membrane to the stratum corneum was two to three times higher than in the control (59). Several loading regimes were applied. Higher levels of friction (over 10 days) resulted in ulceration followed by epidermal thickening; healing was observed at days 3-4 despite continued application of friction. The 10-day severe friction group showed similar but more accentuated changes than the

35-day moderate friction group (hypertrophy of both stratum corneum and other layers: thickening of stratum Malpighii, increased cells in stratum spinosum and stratum granulosum). Increased cellularity in the dermis was also noted. Changes in the 7-day moderate application group were no different from the 14–35 day groups, indicating that the principal changes in epidermal structure take place within several days. The response is interpreted as a means to maintain the structure of the stratum corneum under stressed condition. In the case of severe friction, the epidermis is able to eventually withstand the original stimulus without damage. Another animal study by Carter (60) based on the brushing of the gums of rats reported an increase in the height of the epithelial papillae (measured as difference between maximum and minimum thickness of epidermis) in the stressed tissue.

The results suggest mechanisms and processes for adaptation to frictional stress. The cells at the basement membrane increase in size, density, and speed of transport across the epidermis, increasing thickness of the stratum corneum layer. The thickened stratum corneum means that there is a greater volume through which to distribute the shear load between the skin surface and immediately above the basement membrane. With a greater volume of stratum corneum, shear stress gradients are lower; thus, the skin is at lower risk of failure.

Tension. Tensile loading occurs when skin is pulled in the plane of its surface. For example, closure of a wound with a suture induces tension across the wound. Swelling induces tensile forces in the skin. Tension also occurs when shear stress is present, for example, near adherent scar tissue or at the distal region of a residual limb as the prosthesis is donned.

Results from interface stress studies on persons with amputation support the importance of tension. Prosthetic socket design practice emphasizes the need to design socket indentations on the tibial flares and postero-proximally so as to avoid loading the antero-tibial crest region. Interface shear stress studies by Sanders, et al. (61) produced an interesting finding concerning anterior shear stress and skin tension. Sanders found that anterior shear stresses had a high horizontal force component. In other words, the shear stresses were directed away from the crest of the tibia such that skin over the tibial

crest, a region that was not in direct contact with the socket, was put under tension. Excessive tension, and thus tissue injury, could result in skin that was not even in contact with the socket surface. These findings indicate the importance of the distribution of the applied shear stress on the tibial flare regions and that it influences tension in the skin.

Investigators conducting clinical and animal studies have searched for rules on the threshold for breakdown from tension. The research has been conducted principally with reference to the healing wound. The rate at which surgical wounds initially gain tensile strength is slow. The breaking strength of an incisional wound by the end of the postoperative third week has been demonstrated to be only about 20 percent of intact skin (62). The slow rate of gain in tensile strength is explained physiologically. During the initial weeks, granulation tissue formation is occurring, a period in which a loose matrix of collagen and proteoglycans are synthesized and angiogenesis occurs. However, there is then a rapid increase in tensile strength over the following 3 weeks (postoperative fourth to sixth weeks). The increase in tensile strength is thought to be secondary to collagen deposition, collagen remodeling, and, finally, alteration of crosslinks (22).

Factors that affect skin tension have been demonstrated in rehabilitation practice. The shape of the apex angle of the prosthetic socket to control tibial flare shear stress and thus tension over the tibial crest is an excellent example. As a second example, in treatment of SCI patients undergoing myocutaneous flap surgery, during the operative procedure as well as the perioperative period, tension is avoided by having the patient rest in bed. Slow progressive range of motion is conducted postoperatively, putting tension on the wound.

Clinically, encouragement of skin adaptation to tension is practiced. Tissue expansion procedures commonly used to provide skin for reconstructive surgery provide an example. Sacs inserted beneath the skin are slowly inflated over periods of weeks to months, putting the skin in biaxial tension and increasing its surface area. Once sufficient skin is grown using this method, the defect is removed and the skin closed.

Studies on animals have provided some insight into the physiological changes during tissue expansion. In the epidermis, increases in thickness, mitotic activity in basal cells, and undulations of the

basement membrane were noted (63). In the dermis, a decreased thickness, an increased number of active fibroblasts, and an overall increase in the amount of collagen were reported. The papillary and reticular layers were filled with thick bundles of collagen fibers, and elastic tissues were thickened and compacted (64). Thus, results suggest that while a redistribution of the collagen matrix occurred which increased the skin surface area and thereby relieved skin tension, it was also evident that the makeup of the collagen matrix was modified into a more robust structure.

Tissue adaptation in other collagenous tissues provides insight into collagen adaptation. A model developed by Flint (65) allowed study of changes in tendon, a collagenous tissue that has some of the same collagen types as skin, for different loading configurations. The release of normal distractive forces from the rabbit Achilles tendon resulted in the disaggregation of collagen fibers and increased quantities of nonsulfated proteoglycans. Subsequent tendon repair and restoration of continuity reversed these changes with the reappearance of collagen fibers, decreased quantities of nonsulfated and increased quantities of sulfated proteoglycans. The influence of tension on tendon composition was also examined in regions of tendon under tension versus those subjected to compression (66). Again in this model, surgical manipulations altered the physical forces acting on the tendon and changes were observed as new functional demands were placed on the tendon. Specifically, the type and amount of proteoglycans were found to be a function of loading parameters (tension vs. weightbearing).

Other investigations support a change in structure to appropriately meet new functional demands in tendons and ligaments. In exercised versus control animals, physical training (weeks to months) was found to induce increased mean collagen diameter, fibril number, and fibril cross-sectional area (67). Birefringence measurements have indicated a reorganization of the extracellular matrix components into a structure with greater alignment and more intense molecular packing, accompanied by an increase in tensile strength (68). In swine tendons, exercise resulted in higher resistance to applied loads due to an increase in tensile properties and mass (69). Crosslinking density is correlated with tensile strength of tendons (70), and a shift in the types of

crosslinks in response to exercise has been demonstrated (71).

Thus skin, tendon, and ligament studies all suggest, in response to increased tensile forces, increases in collagen fibril diameters, collagen crosslinking, and sulfated proteoglycans.

CONCLUSION

The knowledge gained concerning skin response to mechanical stress from clinical experience and from basic science studies to date emphasize an important concept. Rather than considering "break-down" as an endpoint, we should instead consider "adaptation" as the endpoint. In other words, our goal in clinical treatment should be to encourage the skin to adapt to become load-tolerant to the high force levels it will be subjected to for the life of the individual with the chronic disease or disability. Adaptation is not optional, it is critical. A new structure that will tolerate the abnormally high force levels the skin will be subjected to must be generated.

Studies from the biomechanical and comparative anatomy literature investigating skin and related collagenous tissues indicate two important concepts. First, skin adaptation occurs. Second, the adaptations are different for different directions and durations of applied mechanical loads. Skin structure and bioprocesses are modified according to the mechanical demands placed on the skin. A goal of rehabilitation treatment should be to encourage the skin to adapt to become load-tolerant to the force levels it will be subjected to for the life of the individual.

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