Basic anatomical principles and functions of soft tissue and bone
General anatomical considerations

Reto Wettstein, Dominique Erni

The musculoskeletal system may be considered as an interconnected system of bones and muscles, which is responsible for locomotion. For detailed histomorphologic analysis, one would differentiate the following tissue units: skin, subcutaneous tissue, tendon-muscle and bone-joint. However, from a functional point of view, a distinction can plausibly be made between a skin-subcutaneous and a bone-muscle unit.

Several physiological functions have been attributed to the skin-subcutaneous tissue unit, such as a mechanical barrier function, preventing the invasion of bacteria and the infiltration of chemicals, homeostatic and thermostatic regulation, motion, respectively gliding as well as cushioning, e.g., by palmar and plantar fat pads. Adipose tissue is specifically involved in energy and vitamin storage, serves endocrine functions, and functions as a stem cell reservoir.

The bone-muscle unit has been studied intensively for its biomechanical properties (stability, motion/movement, force transmission). The two functional subunits—bone and muscle—are interconnected, and their anatomical position is maintained by the fascial system. Neurovascular structures support their function, except in cartilaginous tissue.

The following texts illustrate the specifics of both, the soft tissues and the bone, starting out with the fascial system. Special emphasis is on the basic knowledge and the description of the vascular anatomy, a prerequisite for surgeons dealing with soft-tissue injuries and defects.

Fascial system: a connective tissue framework

Reto Wettstein, Dominique Erni

2.2.1 Introduction

The core of the continuous fascial system, which penetrates and permeates all tissue layers, is formed by bone and periosteum. The fascial system forms a 3-D scaffold responsible for the compartmentalization of the muscle-tendon unit and the differentiation of the subcutaneous tissue into a superficial and a deep layer before it merges into the reticular dermis. The dimensions and strength of these connective-tissue bands and their attachment to the dermis determine the mobility of the skin relative to the underlying structures and, thus, its stability. The main function of the fascial system lies in the maintenance of structural integrity, i.e., the support and protection of the soft-tissue envelope. In case of trauma, the fascial tissue plays an essential role in tissue repair as this framework—rich in vessels—can provide a well-vascularized tissue matrix, allowing for rapid regeneration.

The fascial framework is a continuous syncytium of dense fibrous and loose areolar connective tissue, comparable to the walls of a honeycomb. The neurovascular elements are embedded in this connective tissue and follow the framework that serves as a scaffold down to the microscopic level. If the connective tissue is rigid and tear resistant, such as in intermuscular septa, periosteum, or deep fascia, (i.e., muscle fascia), the neurovascular structures run beside or along it. If the connective tissue is loose, the vessels and nerves run within it as in the superficial fascia of the skin (Fig 2.2-1). Occasionally neurovascular structures and tendons are found in fibrous sheaths or canals within bone, providing stability and protection against bowstringing of tendons. Loose areolar tissue within these tunnels allows the arteries to pulsate and the veins to dilate.

From a pathophysiological point of view, the fascial system can form an anatomical barrier to tumor growth and infiltration. It can also be a site of potential inflammation (e.g., plantar fasciitis) or infection (e.g., panniculitis, cellulitis, fasciitis,) allowing them to spread (e.g., necrotizing fasciitis). Furthermore, the fascial system may constitute a strong limitation in posttraumatic and postsclerotic swelling, initiating a cascade, which leads to the clinical picture of compartment syndrome.
2 Basic anatomical principles and functions of soft tissue and bone

2.2.3 Vascular arrangement

Arterial injection studies of source vessels (segmental and distributing arteries) have proven the existence of 3-D units consisting of skin and underlying deep tissue, forming vascular territories \([1, 2]\). These are called angiosomes (Fig 2.2-1, 2.2-2a–b). On the next level embedded within such vascular territories, the blood supply to the skin is provided by two main sources:

- a direct cutaneous vascular system
- a musculocutaneous vascular network \([3]\).

The cutaneous vascular system runs through structures such as fascia or septa of muscles. The musculocutaneous vascular network consists of three types of vessels:

- **segmental arteries**, which are a direct extension of the aorta. They generally run beneath the muscles and are accompanied by a single large vein and often by a peripheral nerve \([4]\).
- **perforating vessels**, passing through septa or muscles (true muscle perforators). They serve as connections from segmental vessels to the cutaneous circulation. These vessels or perforators form ramifications to supply the muscles with blood \([5]\).
- **cutaneous vessels** consisting of musculocutaneous arteries which run perpendicular to the skin surface, and direct cutaneous vessels, which run parallel to the skin. The latter can be divided into a fascial, subcutaneous, and cutaneous plexus (Fig 2.2-3).

The knowledge of the vascular anatomy integrated within this fascial system is a prerequisite for any surgeon who intends to adequately deal with soft-tissue trauma or major flap surgery.

This vascular system is differentiated into:

- vascular axes and source vessels
- vascular arrangement
- vascular plexuses
- microcirculation
- venous drainage.

This is essential in order to illustrate the different levels of blood flow from the heart to the muscle, subcutaneous tissue, and skin as well as backflow in the venous system, and to appreciate the vascular organization within these tissues, especially the physiologically most active zones for the exchange of metabolites, i.e., the microcirculation.

2.2.2 Vascular axes and source vessels

Starting at the level of the groin and axilla, respectively, the arborization of the major arteries and veins provides source vessels for different flaps that can be isolated for specific indications. The anatomical details of the vascular tree, in particular the one of the lower extremity, is described in chapter 10.3.
Fig 2.2a–b  Angiosomes of the body’s extremities and their importance for flap surgery.

a  Anterior view
b  Posterior view.

1  Groin flap (superficial iliac circumflex artery).
2  Anterolateral thigh flap (descending or horizontal branch originating from the lateral circumflex femoral artery).
3  Lateral supramalleolar flap (lateral malleolar artery originating from the fibular artery).
4  Saphenous flap (terminal branch of the descending genicular artery).
5  Distal medial thigh flap (medial collateral artery originating from the popliteal artery).
6  Medial foot flap (cutaneous branch originating from the medial plantar artery).
7  Medial plantar artery flap, the so-called instep flap (medial plantar artery).
8  Sural artery flap (sural artery with reversed flow).
Interconnections exist at all levels between adjacent vascular territories and can be true anastomosis or choke vessels (Fig 2.2-1). Bidirectional perfusion via vascular connections between adjacent angiosomes may occur, depending on local pressure changes. Thus, compensation is possible in case one branch should be occluded, which permits the transfer of more than one angiosome on a single pedicle, based on its source vessel respectively. In general, the anatomical territory of each tissue in the adjacent angiosome can be included without endangering distal flap perfusion. It is of the utmost importance to know these safe anatomical boundaries of tissue in each layer that can be transferred separately or combined as a composite flap.

### 2.2.4 Vascular plexuses

Beside connecting superficial with deep structures, fascial frameworks present also a horizontal orientation, and so do their accompanying vascular plexuses. The deep muscle fascia is well vascularized with a pre- and subfascial plexus. In contrast, subcutaneous tissue is relatively poorly vascularized with the exception of the superficial fascial layer. Even more superficially, a subdermal, dermal, and subepidermal plexus guarantee an appropriate perfusion of the skin (Fig 2.2-3).

### 2.2.5 Microcirculation

The vascular network between arteries and veins, ie, arterioles, capillaries and venules, forms the zone of the vascular system where most of the tissue oxygenation, nutrition, and metabolite exchange occurs. Insufficient arterial inflow pressure, venous outflow obstruction due to trauma, vascular insufficiency, inadequate surgical tissue manipulation (ie, incision, undermining), hematoma, seroma, and kinking of the pedicle can jeopardize microcirculatory tissue perfusion in zones furthest from the source vessels. This may lead to ischemic tissue damage, resulting in delayed wound healing, dehiscence and necrosis (Fig 2.2-4a–b). This, in turn, increases the risk of infection, which will further aggravate the situation. Maintenance of tissue perfusion in critical situations (Fig 2.2-4c–e) by hemodilution or pharmacological substances has been investigated intensively as has preoperative tissue protection, ie, tissue preconditioning [6, 7].

### 2.2.6 Venous drainage system

There are two systems of perforating veins. Communicating veins are large veins that pierce the deep fascia and connect the superficial venous plexus to the deep venous system. Concomitant veins are small, usually paired, and accompany the cutaneous arterial perforators often present within the fascial system. Another important distinction lies in the distribution of valves. Oscillating, avalvular veins permit the bidirectional flow usually found in smaller, horizontally organized veins, whereas the bigger veins mentioned above are equipped with valves that direct venous return toward the heart. Insufficiency of the venous outflow can be detrimental to the delicate equilibrium of the arteriovenous blood flow. Venous stasis can lead to edema formation and increases the risk of infection, wound-healing disorders, and tissue necrosis.
2.3 Skin and subcutaneous tissue

2.3.1 Skin composition

The skin is kept in place by the fascial framework mentioned before, as can be observed in bodybuilders, where septal, periosteal or muscle fascia attachments that form grooves and dimples become visible. Extensions of the fascial system blend with the collagen fibrils of the reticular dermis. The extracellular matrix of the reticular and papillary dermis, composed mainly of collagen, provides the strength of the dermis. The subcutaneous tissue is formed by adipose cells embedded in lobules within the fascial network and which, in most parts of the body, is divided into a superficial and deep layer by the superficial fascia or so-called Scarpa fascia in the abdomen and Colles fascia in the perineum [8]. In the distal parts of the extremities there is no distinct subcutaneous fascia [9], instead, a barely visible, attenuated fibrous membrane can be found, separating a single layer of subcutaneous fat from the underlying muscle fascia.
In the palmar region of the hand and, respectively the plantar region of the foot, highly specialized tissues are found. In these zones, especially in the foot, which are subjected to shear force, torsion and compression, the skin and subcutaneous tissue present specific features, as an adaptation to bipedal locomotion. The characteristics of plantar skin are as follows: a significantly thicker stratum corneum of 2–4 mm in contrast to 0.04 mm elsewhere, with the presence of a stratum lucidum visible under the light microscope. There are no pilosebaceous units and apocrine sweat glands but an abundance of eccrine sweat glands and, therefore, there are no oily secretions, which would compromise gait. Firm, fibrous septae bind the skin that has a deeper dermal papillary layer with pronounced friction ridges, to the underlying tissues. In addition, a rich supply of sensitive receptors is present. The heel pad functions as a cushion between bone and the overlying skin in order to provide an even distribution of the pressure and to prevent ulcer formation. Loculi of adipose tissue are contained in compartments bound by fibrous septa, which extend from the skin to the calcaneus and the plantar aponeurosis. Although these fat-filled compartments are deformed under compression, the dense fibrous septa prevent an escape of fat tissue from any compartment. The numerous elastic fibers in these loculi assure the return to their original shape.

2.3.2 Clinical implications

The surgical relevance of skin and subcutaneous tissue anatomy is basically defined by the vascular supply and the mechanical strength provided by the different components for wound closure. In healthy, nontraumatized tissue, closure of a single surgical incision does not cause any problems. Contusion, bruising, extensive tissue mobilization, post-traumatic and operative swelling, hematoma or seroma formation as well as underlying diseases such as diabetes mellitus, arteriosclerosis or venous thrombosis can change the balance and cause healing disorders (chapter 4.4). To prevent complications, tissue mobilization should be restricted to an absolute minimum, hemostasis should be optimal, and tissue handling must be gentle (chapter 1). Over bone prominences and in the lower leg, skin perfusion can be critical in comparison with other locations. Multiple, especially parallel incisions should be avoided or carefully planned and the anatomical principles outlined above must be respected in order not to disturb vascularity, thereby risking subsequent necrosis of the soft-tissue cover and skin. In traumatic injuries the amount and extent of tissue damage is often difficult to judge initially and may only become evident after a few days (chapter 5.1, 10.3). Devascularization and contamination increase the risk of infection, which will further compromise wound healing. In cases of soft-tissue defects, a thorough assessment of the wound ground with evaluation of viable tissue and exposure is necessary. In such case debridement (chapter 7.1) of poorly vascularized structures and irrigation (chapter 7.2) of contaminated wounds is essential for further treatment.

From the principles outlined above, it becomes evident that the fascial structures provide mechanical stability and are the ones capable of withstanding any tension associated with wound closure. At the level of the deep muscle fascia, primary closure is indicated in cases of extensive incisions in order to prevent bulging or herniation of the muscle. However, the risk of compartment syndrome must be taken into consideration, and a mesh patch may be useful if a fascial defect is to be covered primarily. The next layer that can resist tension in wound closure is the superficial fascia within the subcutaneous tissue, which should be sutured as selectively as possible in order to prevent necrosis of subcutaneous fat. In addition, an intact layer of adipose tissue between the deep fascia and the skin can prevent adhesion formation. Probably the most stable layer for wound closure is the dermis. Deep dermal stitches can align the wound edges so that an aesthetically attractive intradermal suture can be achieved with minimal tension and so that early removal (4–7 days) of the transdermal suture material is possible in order to prevent stepladder marks on the skin. Contour deformities due to insufficiency of the superficial fascia, adhesion, and stepladder marks are common complaints of the patient postoperatively if everything else went well.
Tendons, just like muscles and nerves, may be considered as specialized structures within a scaffold built by a reticular network of connective tissue—similar to the body-forming fascial system (chapter 2.2), with which it is interconnected—forming the endo-, peri-, and epimysium, the para-, epi-, and endotenon, and the endo-, epi-, and perineurium. This extracellular matrix framework defines tissue and organ architecture, separates cells and tissues into functional units, acts as storage and dissipative component for elastic energy, and serves as the substrate for cell adhesion, growth, and differentiation of a variety of cell types. Histologically, tendons are composed of an extracellular matrix network consisting of collagen fibrils, containing mainly type I collagen, the ground substance primarily composed of proteoglycans, glycosaminoglycans, and glycoproteins, and the cellular elements, mainly tenocytes and tenoblasts. Tendons have a relatively low metabolic rate and a well-developed anaerobic tolerance, which is important for situations of sustained mechanical stress. Correspondingly, they are poorly vascularized and have a slow healing capacity.

Tendons act as a buffer by absorbing external forces in order to limit muscle damage on the one hand, and by bundling and transmitting the force created by contractile proteins of the muscle to rigid bone levers on the other hand. Whereas fleshy muscle insertions do not induce any structural changes in bone, tendinous insertions produce distinct markings such as tubercles or ridges. In order to change the direction of forces (eg, pull), tendons are routed by retinacular fibrous sheaths (ie, pulleys). These sheaths serve as cover over bone prominences or grooves, which can be lined with fibrocartilage. Tendons vary in shape and size, may be flattened (eg, aponeurosis) or rounded, and are found at the origin or insertion of a muscle, or at tendinous intersections.

Three zones can be distinguished in a tendon: the musculotendinous and the osteotendinous junctions with the actual tendon lying between the two. The musculotendinous junction is subjected to great mechanical stress, and muscle tears tend to occur at this level. The osteotendinous junction involves a gradual transition from tendon to fibrocartilage to lamellar bone. This prevents damage to the collagen fibers by bending, fraying, or shearing. The fibrocartilage can act as a “stretching brake” as the cartilage matrix prevents the tendon from narrowing, which normally occurs during stress.

The vascularization of tendons is not very well known and is variable. Vessels originating from the perimysium and periostaeum (intrinsic vasculature), or the paratenon and mesotenon (extrinsic vasculature) can supply the three regions of the tendon. Blood perfusion of tendons is less at junctional sites (Fig 2.4-1), especially in fibrocartilaginous areas, and at sites of mechanical stress by friction, torsion, or compression. This partly explains the propensity of the tibialis posterior, supraspinatus, and Achilles tendon to rupture at specific sites.

Muscles, in contrast to tendons, have a comparatively high metabolic demand and are consequently well perfused with blood. As a general rule, muscle perfusion originates from relatively short, segmental vascular pedicles at sites of relative fixation, and from longer vessels if large gliding surfaces without fixations points are present. Skeletal muscles are almost exclusively formed by muscle cells wrapped in a muscle fascia system. Whole muscle groups are compartmentalized. Muscle tissue reacts to hyper- or hypoperfusion by edema formation, leading to a change in volume. As the fascial envelope forming the muscle compartments is not elastic at all, this will rapidly result in an increase of pressure within the muscle compartment (ie, compartment syndrome).

![Fig 2.4-1](image-url) Muscles, tendons, major vessels, and nerves of the posterior and anterior muscle compartment in the lower leg. Note the sparse vascular supply at the musculotendinous junction.
2.5 Bone

2.5.1 Bone composition

Bone tissue derives from cells of mesenchymal origin. It provides mechanical support to the surrounding soft tissues, defines the shape of the body, and protects the central nervous system. Bone tissue can be formed directly by replacing dense connective tissue, eg, desmal ossification, or indirectly by replacing a preformed cartilaginous template, eg, chondral ossification. After initial bone formation the tissue undergoes remodeling. In the human body this results in a lamellar type of bone, which in certain parts of the body is characterized by a specific osteonal composition. Osteonal organization is typical for the compact bone of the cortical diaphyses, whereas the cancellous trabecular meshwork is characteristic for metaphyseal and epiphyseal regions of long bones. The level of structural organization is influenced by factors such as developmental stage, age, topographical localization, and prevailing mechanical stress. Structural organization and healing response of bone tissue differs considerably between species [10].

2.5.2 Periosteal blood supply

Bone tissue is highly vascularized and its blood supply follows characteristic patterns. The outer third of the cortical bone receives its blood supply from the periosteum and the overlying muscle vascularization (Fig 2.5-1). In addition, substantial intracortical anastomoses between the outer periosteal and the inner medullary microvessels exist [11, 12]. The fundamental importance of periosteal blood supply is reflected by observations in femora of guinea pigs, showing that between 70 and 80% of the arterial supply and 90–100% of the venous drainage depend on periosteal vessel function [13].

2.5.3 Endosteal blood supply

Diaphysis

In long tubular bones, the inner part of the cortex receives its blood supply from the inner vascular system, which is supplied via nutrient arteries that enter either through defined foramina at the diaphyses of long bones or via numerous small vascular branches near the epiphyses. Nerve fibers accompany the nutrient arteries and branch into the intracortical canal system before they finally reach the endosteum and the bone marrow cavity [14]. Many of these nerve fibers are immunoreactive for substance P and calcitonin gene-related peptide, and thus are likely to be related to pain reception [15]. The arteries supplying the bone marrow show a comparable reaction to vasoactive agents as arteries in other parts of the human body [16].

Fig 2.5-1 Periosteal blood supply in sheep bone demonstrated by india ink injection. The outer part of the cortical bone (1) receives its blood supply from vessels (arrows) running in the periosteum (2). Scale bar: 200 μm.

Fig 2.5-2 Endosteal vascular system in ground section of sheep bone demonstrated by india ink injection. Capillary sinuses coming from the medullary cavity (1) form an endosteal vascular system (arrows) near the cortical bone surface (2). Scale bar: 200 μm.
Nutrient vessels enter the diaphyseal cortex through one or multiple foramina, which are often located at the dorsal aspect of long bones, branch towards the proximal or distal end of the diaphysis and provide vascular supply for bone marrow and the inner two thirds of the cortical shell [17, 18]. In the medullary cavity, part of the venous sinuses unite to form a central vein, which drains through a nutrient foramen [19]. Additionally, capillary sinuses form an endosteal vascular system near the medullary cortical surface (Fig 2.5-2) with direct connections to the venous system in periosteum and muscle [19, 20].

**Epiphysis**

Vessels remaining from skeletal growth and development typically form the vascular supply to the epiphyseal bone regions [17, 21]. During growth, the human epiphyseal vascular system is only barely connected to the metaphyseal vascular system by transphyseal vessels [22]. Later in life when the trabecular plate, which represents the epiphyseal scar, is remodeled and the resulting porosity of the bone plate enhances the contact between the epiphyseal and metaphyseal marrow cavities, the connection may become closer [23]. Bones with lifelong persisting epiphyseal scars undergo a change in porosity of the epiphyseal bone plate, which is supposed to potentially seal off the metaphyseal region from the epiphyseal region. An MRI investigation revealed an increased incidence of avascular osteonecrosis of the femoral head in patients with apparently sealed-off epiphyseal scars [24]. Transphyseal vessels, which are more commonly observed in avian than in the human species, have been associated with the spreading of bacteria from metaphyseal to epiphyseal regions, resulting in osteomyelitis [25].

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### 2.6 Regional variations in vascular anatomy

**Authors** Reto Wettstein, Dominique Erni

#### 2.6.1 General aspects

The pattern of blood supply may differ in the various areas of the body in such a way that may be relevant for the restoration of injured soft tissue. The thickness of the skin and subcutaneous tissue as well as the density of the vascular plexus within the fascial system are decisive for the choice of incisions, extent of mobilization of skin, and width-to-length ratio of flaps. The specific characteristics are described below.

#### 2.6.2 Head and neck

This area provides the best perfused skin of the entire body. The arteries are usually accompanied by only one concomitant vein. Due to the close vicinity to the heart, arterial intraluminal pressure is higher than anywhere else in the body. The course of the arteries tends to be undulating. Venular valves are only rarely present, which makes venous outflow vulnerable to increased intrathoracic pressure. The subdermal vascular plexus is extremely well developed, which offers a wide range of choice in repositioning avulsed skin flaps, surgical undermining of wound edges, and the design of random-pattern skin flaps with regard to width-to-length ratio (chapter 10.3). Accordingly, the head and neck area has the highest tolerance against wound infection, unless the wound is contaminated with saliva. In addition, in wide areas of the face and neck, remnants of the original panniculus carnosus muscle can still be found in terms of the platysma muscle and the subcutaneous musculoaponeurotic system, which are located directly beneath the skin and provide an additional, highly vascularized layer of tissue.

#### 2.6.3 Trunk

In the trunk, the pattern of soft-tissue vascularization is determined by the presence of muscles with large surfaces, eg, pectoralis major, latissimus dorsi, rectus abdominis muscle, which can all be used as carriers of cutaneous blood supply especially suited for musculocutaneous flaps. Furthermore, there are also subcutaneous vascular axes, such as the circumflex scapular, the intercostal, the superficial epigastric, and the superficial circumflex iliac artery. The vascularity of the skin is not as good as in the head and neck area, but better than in the lower extremities. The lower in the body, the thicker the vascular walls, and the higher the number of venous valves. Subcutaneous fat is thickest in the trunk, which, therefore, is the area most susceptible to fat necrosis and subsequent infection. On the other hand, this may be an advantage if voluminous tissue transfer is required.
2.6.4 Upper extremity

The upper extremity is well vascularized and thus almost as tolerant against traumatic or surgical lacerations as the head and neck area. This not only applies to the soft tissues but also for the skeletal structures. While the proximal part of the arm is supplied by a musculocutaneous perfusion system, in the distal forearm and the hand—with hardly any muscles—the skin is merely perfused via septal and subcutaneous vascular structures. Nevertheless, the hand belongs to the best perfused parts of the body. As in other acral structures, a high density of functional arteriovenous anastomoses is found in the palm of the hand and the fingers [26].

2.6.5 Lower extremity

The lower extremity shows the poorest vascular perfusion of the body. In addition, in humans the legs show a high susceptibility to vascular diseases such as peripheral artery occlusive disease, varices, or venous insufficiency with microcirculatory disorders, respectively edema formation. The more distal the localization, the more critical the situation. Due to the increased orthostatic pressure in the lower extremity, thickening of the vascular walls and shorter distances between venous valves are found. In the calf, the venous anatomy is characterized by a plexiform configuration of concomitant veins, which makes their dissection difficult. As in the upper extremities, there is no musculocutaneous skin perfusion in the distal third of the lower leg and foot, where the skin and fascial structures provide the only vascularized soft-tissue coverage of bones, tendons, vessels, and nerves [27, 28].
References and further reading


