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REVIEW

Fascia redefined: anatomical features and technical relevance in fascial flap surgery

Carla Stecco · Cesare Tiengo · Antonio Stecco · Andrea Porzionato · Veronica Macchi · Robert Stern · Raffaele De Caro

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Abstract Fascia has traditionally been thought of as a passive structure that envelops muscles, and the term “fascia” was misused and confusing. However, it is now evident that fascia is a dynamic tissue with complex vasculature and innervation. A definition of fascia as an integral tissue has been provided here, highlighting the main features of the superficial and deep fasciae. Wide anatomic variations and site-specific differences in fascial structure are described, coupled with results of our extensive investigations of fascial anatomy. This will enable surgeons to make better decisions on selecting the appropriate fascia in the construction of fascial flaps. The use of the superficial or deep fasciae in the creation of a fascial flap cannot be selected at random, but must be guided by the anatomical features of the different types of fasciae. In particular, we suggest the use of the superficial fascia, such as the parascapular fascio-cutaneous free flap or any cutaneous flap, when a well-vascularized elastic flap, with the capacity to adhere to underlying tissues, is required, and a fascio-cutaneous flap formed by aponeurotic fascia to resurface any tendon or joints exposures. Moreover, the aponeurotic fascia, such as the fascia lata, can be used as a surgical patch if the plastic surgeon requires strong resistance to stress and/or the capacity to glide freely. Finally, the epimysial fascia, such as in the latissimus dorsi flap, can be used with success when used together with the underlying muscles. Clearly, extensive clinical experience and judgment are necessary for assessment of their potential use.

Keywords Fascia · Flaps · Aponeurosis · Connective tissue · Hyaluronan

C. Stecco · C. Tiengo · A. Stecco · A. Porzionato · V. Macchi · R. De Caro
Department of Molecular Medicine, University of Padova, Padua, Italy

C. Stecco (✉)
Department of Molecular Medicine, University of Padova, Via A Gabelli 65, 35127 Padua, Italy
e-mail: carla.stecco@unipd.it

R. Stern
Department of Basic Biomedical Sciences, Touro/Harlem College of Osteopathic Medicine, 230 West-125th St, New York 10027, NY, USA

Introduction

Fascial tissue has become an object of increasing interest, as new surgical approaches have been developed and perfected, such as the use of fascial flaps in plastic and reconstructive surgery. A renewed need for precise definitions and knowledge of the structure of fasciae and their variations are needed. Surprisingly, little attention has been paid to fascia by anatomists throughout the past several centuries [20, 48]. Singer [34] in 1935 wrote: “the dissection methods pay attention to all organs of the body and anatomical atlases bring pictures of them, but the envelops of these organs, the fasciae, are mostly left to the imagination of the students. A correct knowledge of the fascia, however, is as important as a proper knowledge of the organs”. In addition, a large gap exists between anatomists and the surgeons that increasingly incorporate fascia into their surgical procedures. To add to this dilemma, it is becoming increasingly evident that stem cells and other multi-potential cells reside in the fascia. The surrounding connective tissue participates actively not only in the maintenance but also in the healing and repair of underlying organs [21].

It is anticipated that more research and international cooperation on fascial structure and function could occur once precise definitions and accurate descriptions are provided. Ideally, a precise and commonly shared definition for fascia, for the various fascial layers and their main characteristics, would benefit research and enhance clinical practice, allowing easier and more selective approaches to this tissue. This would also facilitate international collaborative research efforts, which is one of the purposes of the present review.

Ambiguity and confusion in terminology

There is little consistent international terminology for classifying and categorizing the fasciae and other connective tissue structures [20]. Different terms are used for the same structure in different countries [48]. For example, for a long time, the term aponeurosis was used by the French anatomists to indicate all fasciae [2, 9], while in other countries this term indicates only a flat tendon. Besides, Bichat [5] divided the aponeurosis into two distinct classes, one serving for the insertion of muscles (aponeurosis of insertion) and the other for the investment or containment of muscles (investing aponeurosis). In reality, all fasciae probably function in both roles. Therefore, this classification should be abandoned altogether. Another example is the term "transverse carpal ligament" of the wrist, a term used in the English-speaking world, but which is termed "flexor retinaculum" in most European countries. Besides, a large gap exists in knowledge and clinical significance of the term fascia. For example, in clinical practice the term "plantar fasciitis" is used to indicate an inflammation of the deep fascia of the foot, which is usually called by the anatomists "plantar aponeurosis" [25]. However, the term "fasciitis" is also used to indicate the infection of subcutaneous tissue [44]. In the 1998 edition of Terminologia Anatomica, the term fascia is used to indicate a sheath, a sheet or any number of other dissectible aggregations of connective tissue [10]. Terminologia Anatomica provides a long list of terms for the definition of fascia. Despite this, it remains difficult to organize and to use these names properly for communicating between various research, educational, and clinical settings. One of the more evident problems is about the existence of the superficial fascia. Many fascio-cutaneous flaps are formed by the superficial fascia. Plastic surgeons speak about the superficial fascia and seek to understand better their histological and biomechanical features. In the most recent edition of Gray's Anatomy [36], it is suggested that the terminology be simplified and to apply the term "fascia" only to deep fascia. This tome recommends that superficial fascia be included as a component of the hypodermis, and considered as "a single layer of panniculus adiposus" or the subcutis. The term "superficial fascia," or fascia superficialis, thus becomes abandoned in its entirety. Additional comments in Gray's Anatomy are telling "Fascia is a term so vague in use that it signifies little more than assemblages of connective tissue large enough to be visible to the unaided eye. The practice of attaching a name to any aggregation that is large enough to be dissected is of dubious value."

Based on a multimodal strategy consisting of keyword searches using MeSH, conference proceedings, peer-reviewed journal articles, textbooks, and the results of our own extensive experience in dissecting fascia, both clinically and in human cadavers, we use the term fascia only to indicate a well dissectible sheath of connective tissue, according to the definition of the Terminologia Anatomica [10], and we propose the following model for fascial tissue (Fig. 1). From skin to the deepest plane, there is first the superficial fascia that divides the subcutaneous tissue into two adipose layers, the superficial (superficial adipose tissue, SAT) and the deep (deep adipose tissue, DAT), and the deep fascia, which envelops all the muscles of the body. These have regional different characteristics dependent upon the region. Beneath the deep fascia is the epimysium, particularly in the limbs and in some regions of the trunk. Skin ligaments, also called retinacula cutis, connect the superficial fascia to skin and to deep fascia, forming a three-dimensional network around fat lobules [20, 23]. Variations occur in different regions of the body that also depend on the physiognomy of the subject, in the content of adipose tissue and in the thickness of the various fascial layers.

Variations in the anatomy of superficial fascia

The superficial fascia (fascia superficialis) is a membranous layer of connective tissue formed by loosely packed interwoven collagen fibers mixed with abundant elastic fibers. Thicker in the trunk than in the limbs, they gradually become thinner in the limbs peripherally [42]. The superficial fascia is homologous to the cutaneous muscle layer (panniculus carnosus) found in other mammals. Indeed, even in the human, muscle fibers can be found in the superficial fascia, particularly in the neck (referred to as the platysma muscle), in the face (the SMAS or superficial muscular aponeurotic system), in the anal region (external anal sphincter), and in the scrotum (the dartos fascia).

Functionally, the superficial fascia can participate in the integrity of the skin and provide support for subcutaneous structures. For example, the main superficial veins reside within the superficial fascia (Fig. 2a), that splits into two sublayers to envelop these veins. The adventitia of these veins is connected with the superficial fascia by thin ligaments, ensuring their patency [7] and preventing

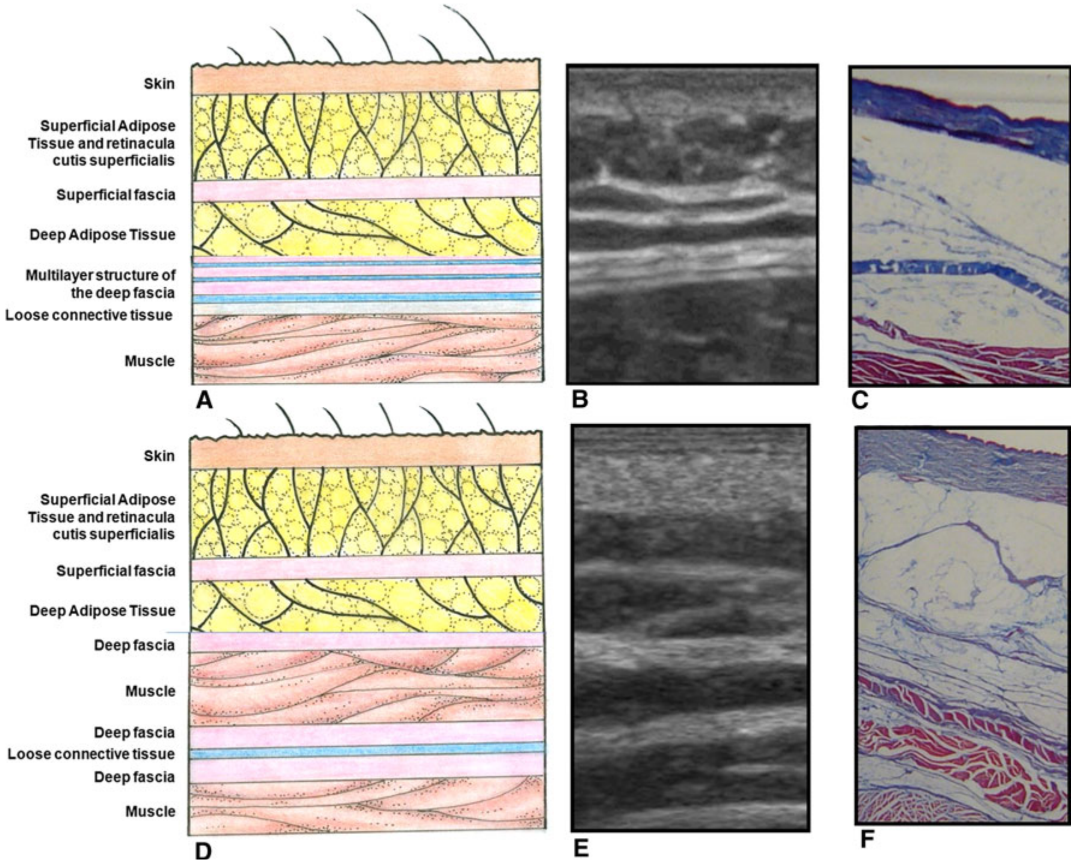

Fig. 1 Basic pattern (**a**, **d**) of organization of subcutaneous layers in the limbs (**a**–**c**) and in the trunk (**d**–**f**). These general models correspond well to ultrasound (**b**, **e**) and histological (**c**, **f**) images. The superficial fascia divides in all the body the subcutaneous tissue into two adipose layers, the SAT (superficial adipose tissue) and the DAT (deep adipose tissue) in the body. Fibrous septa connect the superficial fascia to skin and to deep fascia, forming a three-dimensional network around fat lobules. The deep fascia shows different features according to the particular region: in the limbs it is formed by two or three fibrous sublayers separated by HA, in the trunk the deep fascia is thinner consisting of only one fibrous layer

displacement of veins during movement. In addition, the hypodermal plexus, both arterial and venous, is inside the superficial fascia (Fig. 2b). The arteries of this plexus present many arteriovenous communications that allow shunts to occur that control blood flow through the skin and are used to control body temperature. Besides, the state of distension or constriction of the subcutaneous arteries determines the skin temperatures and skin color in light-skinned individuals. Marked pallor of the skin, which is seen in acute shock, results from vasoconstriction in the arterial plexus of the hypodermis. It is possible that an alteration of the skin color or chronic skin ischemia could be due to alterations in superficial fascia. Indeed we can hypothesize that a fibrotic fascia chokes the arteries inside, reducing skin vascularization. Furthermore, within the superficial fascia, many nervous fibers can be observed.

On bony prominences and at some ligamentous folds, the superficial fascia adheres to the deep fascia. In some regions, the superficial fascia splits, forming special compartments, particularly around major subcutaneous veins and lymphatic vessels, with fibrous septa that extend out to attach to vessel walls. It is apparent that site-specific variations in superficial fascia should be considered in the selection of fascial flaps.

Variations in the anatomy of deep fascia

The deep fascia is a fibrous layer that covers muscle bundles. Two different types of deep fascia can be distinguished: aponeurotic fascia and epimysial fascia. The first type includes the fasciae of the limbs, the thoracolumbar fascia and the rectus sheath. The second is typical of the deep fasciae of the trunk, as well as those of the pectoralis major, trapezium, deltoid, and gluteus maximus muscles.

The epimysial fascia consists of a thin collagenous layer with a mean thickness of 150–200 μm, tightly connected to

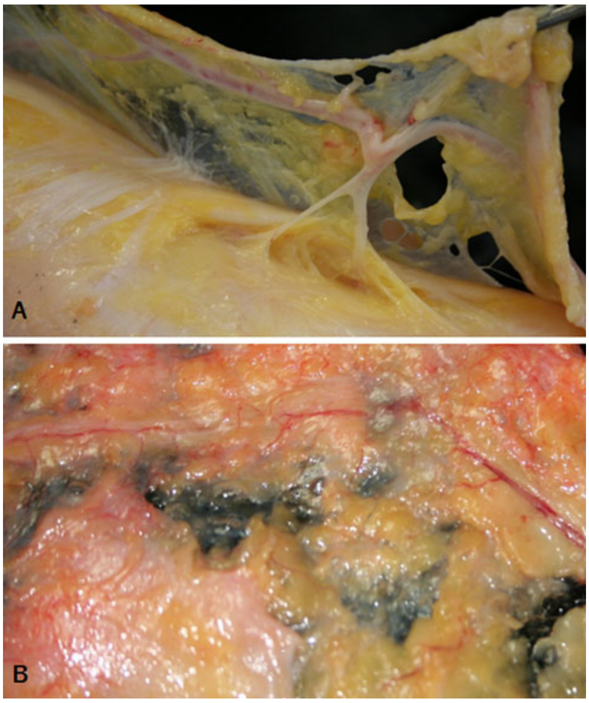

Fig. 2 Superficial fascia and vessels. **a** The superficial fascia of the leg was detached from the deeper planes. It is evident that the saphenous vein is embedded within the superficial fascia and that the perforans vein crosses vertically the deep adipose tissue. **b** Superficial fascia is isolated. The hypodermal plexus is evident inside

underlying muscles by multiple fibrous septa that originate from the inner aspect of the fasciae and penetrate the muscle [37]. Because of such features, it is not possible to separate epimysial fascia from underlying muscles. For this reason, such fascia is used for flaps only in association with its attendant muscle.

The aponeurotic fascia consists of a sheath that has a mean thickness of 900 µm, thinner in the upper limbs, thicker in the lower limbs. It is normally easily separable from the underlying muscles, being connected to them only by some myofascial expansions, more evident around the joints. Under the deep fascia, the muscles are free to slide because of their epimysium and the hyaluronan (HA, hyaluronic acid) present between the deep fascia and the epimysium itself [41]. According to Cruveilhier [9], all the aponeurotic fasciae are tensioned by specific myofascial expansions (i.e., the lacertus fibrosus is a tendinous expansion of the biceps brachii muscle which stretches the antebrachial fascia), or dedicated muscles, such as the tensor fascia lata, the palmaris longus, etc. The connection between fascia and muscle/tendon occurs only in well-defined points that could be mapped. If we analysed all of these myofascial expansions, we would note that they are disposed according to their spatial planes, providing tension to the aponeurotic fascia in a precise way, according to the direction of movement [40]. The aponeurotic fasciae are formed by two or three layers of parallel collagen fiber bundles, each layer having a mean thickness of 277 µm. Adjacent layers show different orientations of the collagen fibers, creating an angle of approximately 78° [4]. Histological analyses indicate that the volume of total collagen is about 18 % and elastic fibers, less than 1 % in the deep fasciae of the lower limb, and slightly more in the upper limb, where they form an irregular meshwork.

Wavreille et al. [47] demonstrate that the deep aponeurotic fascia is well vascularized. In particular, they find in the brachial fascia a rich vascular network located strictly between the deep and the superficial aspects of the fascia. The internal diameter of these small arteries was between 0.3 and 0.5 mm. These authors also find many anastomoses between the various arterioles and the abundant venous network. The deep fascia also has well-developed lymphatic channels [3] with a surprisingly high rate of flow of lymphatic fluid flow.

The multilayered structure of the aponeurotic fascia and the paucity of elastic fibers endow that particular fascia with specific mechanical properties. It is a tissue with strong resistance to traction, even when stretched in different directions [25, 39, 46]. The spatial orientation of the collagen fibers endows the aponeurotic fascia anisotropic characteristics. This means that the fascia is stiffer along a longitudinal direction in respect to a transverse one. Hurschler et al. [17] report an average structural stiffness per unit width of the aponeurotic fascia of 50.9 ± 33 N/mm in longitudinal direction, and of about 46.4 ± 16 N/mm in transversal direction, confirming that the fascia is stiffer along the longitudinal axis of the limb. These findings permit us to assume that the fascia in a transversal direction adapts to muscular volume variation, while in a longitudinal direction, it is similar to a tendon, transmitting the force from one segment to another. This facilitates the connection between the hip, the knee, and the ankle. For example if the gluteus maximus contracts, because of its insertions into the fascia lata, it permits it to stretch. The fascia lata transmits these forces along the iliotibial band in za longitudinal direction, providing tension along the anterolateral portion of the crural fascia and the anterior knee retinaculum. In contrast, the same fascia lata is able to adapt during the contraction of the quadriceps muscle, permitting variations in transverse sections of the muscle. If the fascia loses this adaptability, the underlying muscle cannot contract correctly. In addition, the stiffness of the aponeurotic fascia varies in different regions of the body. For example, our own research [39] and the work of Hurschler et al. [17] demonstrate that samples of the crural fascia taken from the anterior compartment of the leg are stiffer than samples originating from the posterior one. This finding corresponds well to the evidence derived from clinical practice, considering, for example, the fact that the anterior compartment syndrome occurs more frequent than does the posterior one.

The analysis of the mechanical response of the aponeurotic fascia to uni-axial loading tests demonstrates typical non-linear behavior, similar to that of tendons [25]. In particular, we can recognize a toe portion, a linear portion, and a failure portion. Indeed, due to the un-crimping of collagen fibers and elasticity of elastin, the initial portion of the stress–strain curve has a high deformation/low force characteristic. Then, over 4 % all the collagen fibres are oriented in the direction of the load and are tensed. Therefore, for each increase of applied strain, the fascia responds with a corresponding increase in stress. Physical rupture of the fibres commenced over a nominal strain of about 12 %. It is possible that the deformation of up to 4 % is physiological. It allows volume variation of muscles during their contraction. Up to 4 %, the fascia becomes rigid, and thus is in a perfect state to transmit forces at a distance. In the chronic compartment syndrome the adaptation of deep fascia is probably reduced.

Because of these properties, the aponeurotic fascia provides an ideal surgical patch, above all, when a thin, pliable, but resistant coverage for the reconstruction of gliding surface is needed [49]. It is also evident that the mechanical properties of the aponeurotic fasciae differ among the specimens considered, the strain level imposed, the anatomical location and the collagen fibres arranged and oriented. Consequently, we suggest that different fascial flaps have to be used in specific ways. The orientation of the collagen fibres and the main lines of forces acting into these fibrous bands must be taken into consideration.

Fine structure of fascia and its complexities

Recently, it has been documented that fascia is a far more complex structure than previously realized. It is now beginning to be recognized that it is critical for tissue maintenance, and that it is key to tissue health, with an active role in recovery from injury. Besides, the superficial and deep fascial layers have independent vascular networks. There are extensive vascular arcades with perforators that traverse the fascial planes [3, 32, 33]. In the last few years, a number of studies have demonstrated the presence of many free, encapsulated nerve endings, particularly Ruffini and Pacini corpuscles inside the deep fasciae [8, 38, 43], although differences exist dependent upon anatomic region.

A recent work has highlighted that the deep fascia is rich in HA. Hyaluronan is present within deep fascia and also in the layers surrounding muscles [18, 24, 29]. In skeletal muscles, HA is distributed in a heterogeneous pattern in the perimysium and endomysium. Perivascular and perineural fasciae also contain prominent levels of HA. Hyaluronan occurs not only as individual molecules but also bound to proteins and proteoglycans. These form macromolecular complexes that contribute to the structural and mechanical properties of fascia. Hyaluronan is a very high molecular weight (HMW) matrix glycosaminoglycan (GAG) polymer ($>10^7$ Daltons) found mostly in the extracellular matrix (ECM) between and around cells [19]. It is a shock absorber within the synovial capsule of joints. It provides the structure as well as turgor to the aqueous of the eye, protects fetal vessels from compression in Wharton's jelly of the umbilical cord. HA provides the moisture to skin, with its large volume of solvent water, as much as 10,000 times the volume of the original material. Hyaluronan is a lubricant as it glides over skeletal muscle. The previous findings of HA between aponeurotic fascia and muscle and inside the various sublayers of the aponeurotic fascia suggest that it is a key element in the gliding of fascia in respect to the underlying muscles, and between the different fascial sublayers. It is likely that these gliding interactions are influenced by the composition and efficacy of the HA-rich instructional matrix. Changes in this HA-rich matrix could contribute to the pain, inflammation, and loss of function, and may be critical for these pathologic changes. It is also likely that the aponeurotic fasciae and the HA-rich layer between fascia and muscle contain reservoirs of stem cells and multipotential cells that actively participate in the maintenance, repair, and regeneration of underlying structures. The HA plays an important role during the earliest stages of wound healing, opening up tissue spaces through which cells can travel, and bound to its receptors, confers motility upon cells by interacting with the cytoskeleton [45]. Hyaluronan is particularly prominent during embryogenesis, in tissues undergoing rapid growth, and whenever repair and regeneration occur [20, 35]. Finally, the fragmented HA, a reflection of tissues under stress, is highly angiogenic, inflammatory, and immunostimulatory [26, 49]. All these functions of HA help to explain some of the results of fascial flaps and their use in covering wounds and in filling a variety of defects.

Fascial flaps in surgery

For many decades, it has been a practice to provide a fascial flap in surgery. The fascio-cutaneous flap for surgery of the lower limb was described in a landmark paper by Pontén in 1981 [31]. Fascio-cutaneous flaps comprising skin, fat, and deep fascia have been successfully used to

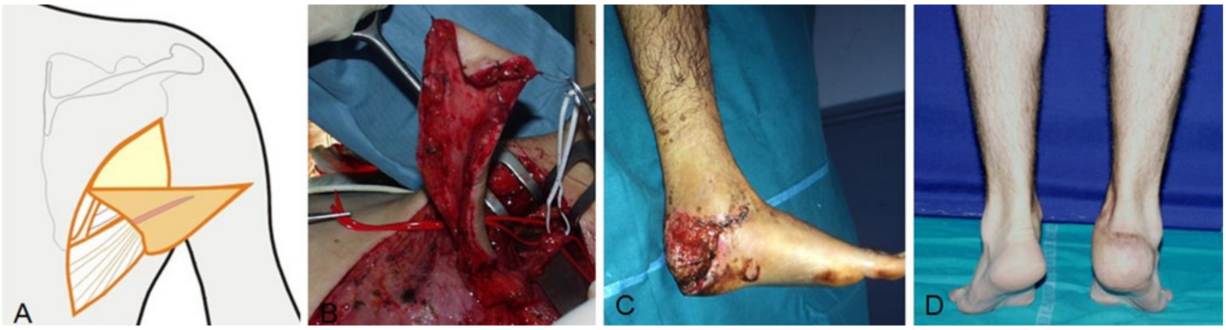

Fig. 3 Parascapular flap (**a** scheme of the flap; **b** dissection technique). This flap is composed of the skin and of the superficial fascia of the parascapular region. The superficial fascia in this region is thick, well vascularized and well innerved. These features facilitate preparation of a perfect flap for covering weight-bearing surfaces, such as the heel (**c** and **d** reconstruction of the heel with a parascapular flap, pre- and post-surgery)

close a variety of defects of the limbs, trunk, and of the head and neck. There are multiple advantages of these flaps: they help restore the blood supply, enhance the rate of healing, and aid in restoring function more quickly. Skin perforator flaps represent a technical advancement over conventional skin flaps because of improved vascularity. This well-known quality gives the fascio-cutaneous tissue transfer the same ability to heal difficult defects as does the more traditional muscle flaps. In fact, when used as pedicles or free, they are able to cover large soft tissue defects involving bony exposures that carry a high risk for infection. Recent literature documents the major advantage of using a fascio-cutaneous reconstruction in terms of decreased incidence of bone infection, good coverage and highly aesthetic results, giving to the muscle flap functional recovery of the face or limbs, e.g., Volkman contractures or revitalization of the facial nerve [15, 50].

In addition, the fascio-cutaneous flaps are able to minimize donor site morbidity, preserve muscle integrity and function. They can be used as rotational or advanced flaps, even when based on a single perforator vessel. Fascio-cutaneous flaps are commonly used as "propeller" rotational flaps when suitable perforator vessels are available in the proximity of the tissue defect [6, 30]. Because of recent developments in microsurgical techniques, such fascial flaps can be transferred to any anatomical site. This has increased even further the use of fascial flaps. With the term fascial flap we include a variety of flaps that have completely different anatomical bases. Indeed some flaps use the skin with the hypodermis up until the superficial fascia. Others are focused into the deep fascia, with or without the underlying muscle. Correct assessment of fascial anatomy would permit a more accurate selection of the fascial flap for each individual situation. For example the aponeurotic fascia is richest in HA and provides a perfect plane for gliding in respect to underlying structures, while the superficial fascia provides a more adhesive surface during surgery. Therefore, a fascio-cutaneous flap including the superficial fascia would be perfect for weight-bearing surfaces, because this fascia is well vascularized and well-innervated, and has the capability to integrate and adhere to bony surfaces, such as the heel or metatarsal bone (Fig. 3). The most frequently used superficial fascia for inclusion in a fascial flap is the overlying superficial fascia of the parascapular region [13]. These flaps reduce the bulk effect produced by a muscle flap, without the drawback of the sliding of a thick muscle flap over the bony surface. Moreover, this kind of flap may also promote progressive proprioceptive recovery. The rich innervation of the thoracodorsal fascia that is included in the scapular or parascapular fascio-cutaneous free flaps could provide favorable tissue reconstruction in such weight-bearing areas or areas exposed to excessive wear where there is a high risk of failure. In contrast, if a critical anatomic area with exposure of tendons, joints or nerves (e.g., the dorsal and volar aspect of the hand, wrist, elbow, knee or foot), the fascio-cutaneous flaps formed by aponeurotic fascia are considered the best option (Fig. 4), with their capability to preserve movement, limit scar adhesion over the surfaces of sliding tendons, even in the absence of the tendon sheath [11, 16, 27]. In addition, the aponeurotic fasciae, such as the fascia lata, can be used alone as a mesh. A number of investigators [1, 28] have documented that the biological mesh provided by the fascia lata is more resistant to infection and is more easily integrated into the new site, in contrast to artificial meshes. It has been observed that the biological repair is virtually free of discomfort, whereas artificial meshes, particularly those that contain tantalum, may become painful. Efficient regeneration of the fascia lata has long been recognized [12] and is well documented. Once placed, it rapidly becomes a component of the new site, a property that is very useful for the repair of abdominal hernias [14]. Another use of the aponeurotic fasciae is in interposition arthroplasty. In this surgery the

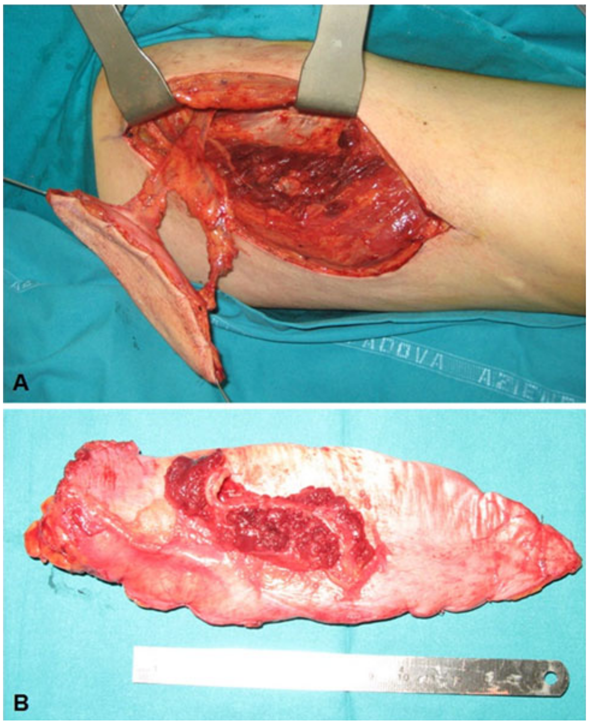

Fig. 4 Preparation of a fascio-cutaneous flap using the fascia lata (**a** dissection technique, **b** isolated flap). The use of the deep fascia of the limbs is indicated. This is used to cover exposure of tendons, joints or nerves because of its capability for preserving movement and for limiting scar adhesion

fascial flap is placed between the damaged surfaces of the joint, creating a false joint. This surgery has best results in younger people with healthy tissue surrounding the joints [22].

In contrast, the epimysial fasciae are too thin and too firmly attached to underlying muscles to be used alone. Deep fasciae of the trunk can only be utilized when underlying muscle is included in the construction of a muscle flap, such as the latissimus dorsi flap. These flaps also provide surgeons with additional reinnervated muscle procedures in functional reconstruction of difficult areas and following complex injuries.

Conclusions

The use of the superficial or deep fasciae in the creation of a fascial flap cannot be selected at random, but must be guided by the anatomical features of their different types. In particular, we suggest the use of the superficial fascia, such as the parascapular fascio-cutaneous free flap or any cutaneous flap, when a well-vascularized elastic flap, with the capacity to adhere to underlying tissues is required, and a fascio-cutaneous flap formed by aponeurotic fascia to resurface any tendon or joints exposures. In contrast, the aponeurotic fascia, such as the fascia lata, can be used as a surgical patch if the plastic surgeon requires strong resistance to stress and/or the capacity to glide freely. Finally, the epimysial fasciae, such as the latissimus dorsi flap, can be used with success when used together with underlying muscles. Clearly, extensive clinical experience and judgment are necessary for assessment of their potential use.

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